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MEET THE ATOMS

A POPULAR GUIDE TO MODERN PHYSICS

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MEET the ATOMS

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MEET the ATOMS

A POPULAR GUIDE TO MODERN PHYSICS

BY

O. R. FRISCH

NEW YORK

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1947

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INTRODUCTION

MODERN DEVELOPMENTS IN ATOMIC RESEARCH, beginning with Roentgen's discovery of X-rays fifty years ago, have aroused the interest of many who are far removed from the circles of professional scientists.

Every physicist fortunate enough to work in this field is filled with gratitude and reverence in contemplating the marvels revealed to us by the realm of atoms and he awaits further developments with great eagerness.

The layman is usually more interested in the practical vistas opened up by these new insights and discoveries. Depending on his present degree of acquaintance with the fundamental questions and his own temperament, he is more or less inclined to let his fancy run wild. There is hardly another branch of science so afflicted with the babble of mystical conclusions and fanciful accounts dealing with the existence and behavior of atoms. Therefore a book is of great value if it can give the nonprofessional a clear, intelligible answer to the question, "What is an atom and how does it reveal itself?"

Meet the Atoms, by Dr. O. R. Frisch, fulfills this task with unusual success and it is, consequently, a distinct pleasure to me to offer this introduction to his book.

In relatively small compass he deals with all the essential experimental and theoretical questions—even including the concepts of quantum mechanics. The reader is taken cor-

INTRODUCTION

hally by the hand, as it were, and guided through a land beloved by the author and known to him in exact detail. The attentive reader during this tour will also learn how the scientist achieves his aims of receiving the clearest possible answers to questions posed.

New facts are always related to previous knowledge. Wherever possible, fundamental experiments are described in vivid fashion, aiding comprehension enormously and achieving very lively presentation of the subject. A very high scientific level is united with an easygoing, almost breezy style.

The layman prepared to think along with his reading will be amazed at the difficult problems made intelligible in relatively simple form, without detracting from their scientific accuracy. In this respect the book makes one think of the fine classic lectures by Tyndall. Furthermore, every biologist interested in physics, every teacher or advanced student of physics can acquire very extensive knowledge of the field from this book.

In our times the wide diffusion of knowledge concerning the problem of the atom and atomic energy is of immense importance. *Meet the Atoms* is extraordinarily well suited for this goal, and I am confident it will find a large and grateful audience.

LISE MEITNER

PREFACE

WHEN I FIRST started to write this book, about three years ago, the atomic bomb had not yet been achieved. Most people I knew had only the vaguest notions about atoms. I remember talking to a dealer in fish who asked me jokingly where we got those atoms we split at our laboratory. When I told him that everything around us was made of atoms he looked surprised. When I added that he and I were made of atoms he acted skeptical. But when I said that even the fish he sold consisted of atoms, he grinned. He knew better.

Some of my friends knew more about atoms. They knew that atoms are awfully small and that there are billions (or is it trillions?) in a drop of water. They had heard that each atom was itself a complicated structure, a kind of solar system, with several electrons whirling around a central nucleus like little planets. Some of them had even heard that the nucleus itself was composed of anything up to two hundred protons and neutrons. But none of them knew how physicists arrived at such statements.

It happens that I am an atomic physicist; it is my job to study atoms—the way they act on each other and the parts of which they are composed. For me, all these things are pretty real. There are of course some statements concerning atoms which are fairly new and not yet certain; but many of them, in my view, are as certain as that the chair on

which I sit is yellow. There are, however, statements which have a different character, like the one about the electrons whirling around the nucleus. If you ask me whether I really believe this, I should have to answer that an atom is in some ways like a small planetary system, but in other ways quite different, and that there is really no way to describe it completely in terms of our everyday experience. I shall try to show you later in this book why it is that I have to give such vague answers to certain questions.

Statements of this hesitating kind have received a lot of attention, and much publicity was given to such things as the uncertainty principle, the acausality of atomic events, relativity, and so on. People grew bewildered by these signs of apparent diffidence among the physicists, and there was a growing belief that atomic physics was approaching bankruptcy, that all its assertions about atoms were nothing but fanciful speculations.

The atomic bomb dispelled this belief. A science which could flatten a town at one stroke must be right. After that most people were ready to believe almost anything about atoms that a physicist would tell them.

I started this book with the idea of showing people that atomic physics was far from bankrupt. After the atomic bomb was launched I felt that the opposite message was more urgent: that atomic physicists are not supermen. Surprisingly enough, I did not have to change the plan of the book.

I shall try to show you in this book that atoms are not really so awfully small. I wish to show that there are various methods for detecting effects of single atoms, even for making them visible after a fashion. Moreover, that there are several straightforward ways of finding out how many atoms there are in a drop of water (provided you tell me

how big a drop) and that they all give quite accurately the same result. I also wish to describe the kind of evidence which indicates that atoms are in some ways like little planetary systems, and the reasons why we think that in other ways they are quite different. I shall tell about the methods through which we have learned something about the parts of which atomic nuclei are made, and why it is that we don't know much yet about their inner structure.

But above all I want to show you how we physicists do these things. You will see that no particularly small and delicate instruments are required to study atoms, and that these studies do not require unusual skill. I want to dispel the belief that the kind of arguments we use cannot be understood without the use of higher mathematics, although I must admit that mathematics is often needed to make the argument precise. In short, I want to convince you that the job of the atomic physicist is just an application of common sense to the planning and analysis of observations that can tell us something about atoms, and is in no essential way different from the job of a naturalist or an astronomer.

Physicists, like members of other professions, have gradually developed their own language. Some of the terms they have created or endowed with new meaning are useful, and I have used them rather than try to replace them by lengthy circumlocutions made up of familiar words. The trouble is, we physicists are so used to that language that we often do not notice that a given word is not used in ordinary language, or that it has a different meaning. I have made an honest effort to keep the technical terms to a minimum and to explain all those I have to use, but some may have slipped in unexplained.

For those of you who like to know exactly how a thing

is done, I have described several experiments in detail, including the calculations needed to arrive at the final result. If you are not interested in the details, skip them; they are not needed later.

Physics, perhaps more than any other science, is a closely woven fabric in which almost any two facts are connected by some logical thread. If a group of facts is snipped out and presented, there are bound to be many loose ends, however skillfully the cutting is done. I have tried to present primarily those facts from which direct conclusions concerning the properties of atoms can be drawn. Sometimes I have followed one of the loose threads for a bit if I thought it might interest you. In many cases I had to resist the temptation of following a side line which would lead me too far away from the main subject. For the same reason I can no more than touch upon the practical applications of atomic physics. They have been treated in many good books and articles.

Physics is difficult, "far too difficult for the physicists," as a famous mathematician once remarked. You may find that many things in this book require some hard thinking. I believe that this is unavoidable if you want to get more than a very superficial knowledge of atoms. Some of my friends warned me that a book which asked the readers to think wouldn't sell many copies. I have a better opinion of the American public.

O. R. FRISCH

CONTENTS

INTRODUCTION <i>by Lise Meitner</i>	v
PREFACE	vii
I. GENERAL SURVEY	3
II. ATOMS ON YOUR WATCH DIAL	11
III. CRYSTALS: ATOMS IN RANK AND FILE	17
IV. ELECTROMAGNETIC WAVES	26
V. THE COLORS OF THE RAINBOW	35
VI. X-RAYS	46
VII. MORE ABOUT X-RAYS	57
VIII. HOW MUCH DO ATOMS WEIGH?	63
IX. THE OIL DROP EXPERIMENT	74
X. ABOUT WEIGHTS AND MEASURES	81
XI. THE LIBERATION OF THE ELECTRON	92
XII. LIGHT, TOO, CONSISTS OF "ATOMS"	103
XIII. SOME ELEMENTS ARE REALLY MIXTURES	113
XIV. RADIOACTIVE ATOMS	124
XV. PROBING THE CORE OF THE ATOM	136
XVI. MATTER AND WAVES	147

XVII. THE ATOMIC NUCLEUS	162
XVIII. MACHINES FOR ATOM-SMASHING	173
XIX. MASS AND ENERGY	188
XX. THE MYSTERIOUS STRANGER	202
XXI. ATOMIC POWER	214
INDEX	224

LIST OF FIGURES AND PLATES

FIGURES

1. A CRYSTAL OF SODIUM CHLORIDE	18
2. PATTERNS FORMED BY STEEL BALLS	20
3. X-RAYS AND THEIR DIFFRACTION PATTERNS	22
4. THE COMBINATION OF FORCES	28
5. DEFLECTION OF COMPASS NEEDLE BY ELECTRIC CURRENT	31
6. RADIO WAVE	33
7. DIFFRACTION OF LIGHT PASSING THROUGH GRATING	37
8. A PRISM SPECTROGRAPH	41
9. X-RAY SPECTROMETER (<i>Bragg's Method</i>)	47
10. X-RAY WAVES DEFLECTED BY ATOMS	49
11. ARRANGEMENTS OF CHLORINE AND SODIUM ATOMS	68
12. ELECTROLYSIS	69
13. MILLIKAN'S OIL DROP EXPERIMENT	75
14. THE EDISON EFFECT	92
15. A HOMOGENEOUS, MAGNETIC FIELD	99

16.	MEASUREMENT OF PLANCK'S CONSTANT THROUGH STUDY OF PHOTOELECTRIC EFFECT	107
17.	EXPERIMENTS WITH ALPHA PARTICLES	127
18.	THE NATURE OF ALPHA PARTICLES	129
19.	A SIMPLE CLOUD CHAMBER	133
20.	LEFT: A SPIRAL; RIGHT: SERIES OF CIRCULAR ARCS WITH DECREASING RADIUS	144
21.	CIRCULAR WAVE PATTERNS	151
22.	FIRST APPARATUS FOR DISINTEGRATION OF ATOMIC NUCLEI	166
23.	LEFT: BELT CONVEYER; RIGHT: VAN DE GRAAFF BELT GENERATOR	176
24.	CYCLOTRON MAGNET	181
25.	CYCLOTRON	182
26.	DIAGRAM OF A MASS SPECTROGRAPH (Aston)	191

PLATES

		END PAPER
1.	DIFFRACTION OF LIGHT BY SCREENS	
2.	LAUE PATTERN OF ROCK SALT SHOWING DIFFRACTION SPOTS	"
3.	THREE DIFFERENT LINE SPECTRA	"
4.	CLOUD CHAMBER AFTER EXPANSION	"
5.	CLOUD-CHAMBER PHOTO OF ALPHA PARTICLES	"
6.	THE SPLITTING OF A NITROGEN NUCLEUS	"
7.	TRANSFORMATION OF A GAMMA QUANTUM INTO TWO ELECTRONS	"

MEET THE ATOMS

A POPULAR GUIDE TO MODERN PHYSICS

I

GENERAL SURVEY

IN THIS CHAPTER I shall give you a general outline of the material I am presenting in this book, and of my procedure. There is no need to read this chapter with great concentration or to try to memorize any of the explanations given here. Everything I say here will be said again later. This is merely like the prospectus of a South Sea trip; it tells what things you can expect and what course the journey is going to take.

Atoms are everywhere around us. All material bodies consist of atoms. In solid bodies the atoms are packed close together; in liquids they have just enough room to slide past each other; in gases each atom has plenty of room for itself. Atoms are always in motion, the more vigorous the motion the hotter the body. In a gas each atom moves in a straight line until it strikes another atom and is deflected; some of them strike the wall and rebound, and the sum total of those millions of little impacts constitutes the pressure which a gas exerts on the walls of its container. In a liquid the atoms just mill around; in a solid they sit and tremble—not from fear but because they are constantly being jostled by atoms around them.

In a piece of pure gold or pure aluminum all atoms are alike; but gold atoms and aluminum atoms are not the same. In the first place, it was shown by chemists that they have different weight; gold atoms are more than seven

times as heavy as aluminum atoms. The lightest atoms of all are those of hydrogen (an inflammable gas), and chemists use the weight of one hydrogen atom as a unit for expressing the weight of other atoms. For example, since an aluminum atom is 27 times as heavy as a hydrogen atom they say that aluminum has the "atomic weight" 27.

Gold, aluminum, and hydrogen are called elements, because they consist of atoms which are all alike. Most substances consist of several kinds of atoms and are called chemical compounds. Water, for instance, is a compound of hydrogen and oxygen (the life-giving element in air); it contains twice as many hydrogen atoms as oxygen atoms, and consists of little clusters, called water molecules, each of which is made up of two hydrogen atoms and one oxygen atom. A sugar molecule is a cluster of 22 atoms of hydrogen, 11 atoms of oxygen, and 12 atoms of carbon (soot and graphite are nearly pure carbon). Even in elements the atoms may be arranged in little clusters known as molecules; for instance, in hydrogen the atoms fly around in clusters of two, called hydrogen molecules.

Atoms are not the smallest things known to physicists. Each atom in turn consists of several parts—a nucleus and one or more electrons. Electrons—as the name implies—are electrically charged with the kind of electricity commonly called negative; the nucleus is positively charged. Electrons, all carrying the same charge, repel each other, but they are attracted by the nucleus which has the charge opposite that of the electrons. The electrons may be pictured as going around the nucleus in circles, as the planets circle around the sun. However, we shall see that this picture does not tell the whole story.

The positive and negative charges inside an atom exactly balance each other so that the atom as a whole appears

electrically uncharged. However, sometimes an atom loses one or more of its electrons and it will then appear positively charged; such an electrically charged atom is called, in brief, an ion. There are also negatively charged ions, consisting of atoms which have caught extra electrons.

Electrons are very light; an electron weighs only about $1/1830$ of one hydrogen atom. All electrons are alike, whether they belong to a gold atom, an aluminum atom or any other. The only difference lies in their number: an aluminum atom contains 13 electrons, a gold atom 79. Nearly all the weight of an atom is concentrated in its nucleus, which is very much smaller than the atom itself. Atoms have diameters of about one hundred-millionth of an inch; nuclei are more than ten thousand times still smaller. Yet they in turn are composed of even smaller parts, called protons and neutrons. The lightest nucleus of all, that of the hydrogen atom, consists of just one proton; the heaviest nucleus occurring in nature consists of 92 protons and 146 neutrons. Neutrons are very much like protons, only they have no electric charge, while a proton has a positive electric charge, of the same strength as the negative electric charge of an electron.

In Chapter II I shall show you that certain atoms can singly produce visible flashes of light, which you can observe if you have a watch with a luminous dial and a magnifying lens. On this phenomenon can be based a method for counting the number of atoms in known amounts of certain elements, thereby determining the weight of a single one of those atoms. The numbers you get in this way are very large and the usual way of expressing them by such words as million, billion, trillion becomes very clumsy; I shall therefore show you the physicist's way of writing large numbers, which is much simpler and very easy to use in

calculations. My advice is that you should spend half an hour practicing this system, because it will make it much easier for you to follow the numerical examples later in the book. But if you have a strong dislike for numbers, you may skip all calculations; they are not essential for the understanding.

In Chapter III I shall speak about crystals. They are of great interest to the atomic physicists because they consist of atoms arranged in a regular pattern. By sending a beam of X-rays through a crystal one can get fairly detailed information on the arrangement of the atoms and thereby on their number in a crystal of given size. Most of Chapters IV and V is devoted to an explanation of electromagnetic waves such as radio waves, light waves, and X-rays. The light rays and X-rays sent out by atoms are messages which the physicist has to decode in order to learn about the internal structure of atoms, and methods for the accurate measurement of the wave lengths of these radiations are therefore of great importance. In particular, the X-rays are an extremely valuable and versatile tool of the atomic physicist. In Chapters VI and VII I shall describe in considerable detail how the number of atoms in a given crystal of sodium chloride (kitchen salt) can be measured with the help of X-rays, and I shall also give some additional facts about X-rays, which are of importance for our knowledge of atoms.

Chapter VIII introduces some of the simple facts of chemistry and shows how it is possible, with the help of these facts, to determine the weight of a single atom of hydrogen from results obtained in our previous chapters. This chapter also brings evidence for the existence of electrically charged atoms (ions). It is shown that ions always carry either a certain "fundamental charge" which is always

the same, or a whole multiple of that charge. Chapter IX shows that the same is true of small drops of oil and describes how the fundamental charge can be measured, and how this measurement can be used to check the previously determined weight of a single hydrogen atom. It also discusses the electrical character of the forces which bind atoms together in chemical compounds.

Chapter X discusses the system on which measurements are based in physics and why physicists prefer to use centimeters and grams rather than inches and ounces. It also describes the basic properties of electric charges and currents, and the way in which electric quantities are measured in the "absolute system." In this chapter atoms are hardly mentioned, but some of the concepts explained, particularly the concept of the electric potential, are very important for what follows. Chapter XI describes some of the simple experiments which led to the discovery of free electrons (the basis for the whole vast enterprise of modern electronics) and shows how their mass and velocity can be measured.

Chapter XII contains the first explicit discussion of that very important aspect of nature which led to quantum theory. While light is an electromagnetic wave, it is shown that a beam of light behaves in some ways like a stream of tiny particles, called photons. The amount of energy carried by a single photon can be measured, as I shall show. Explained, too, will be the way in which physicists are trying to reconcile the two different aspects of light (and any electromagnetic radiation), the wave aspect and the photon aspect.

Chapter XIII returns to the problem of finding the weight of single atoms and describes a way of doing this which is different from those previously described. The

methods described in Chapters II, VI, and IX give only the average weight of a certain type of atom. Going beyond this the method discussed in Chapter XIII allows one to find out whether all the atoms in a given element have the same weight, and I shall show that there are indeed elements which are mixtures of several different kinds of atoms, or, as we say, of several isotopes. In addition, we learn something about the number of electrons in an atom, at least for the three lightest elements.

In Chapter XIV I tell about the so-called alpha particles which are being sent out all the time by radioactive elements, for instance, polonium. Through a number of simple experiments it can be shown that these alpha particles are fast-moving nuclei of the element helium (a light gas, used for filling airships). This proves that an atom can transform itself into an atom of a different chemical element; of course only atoms of radioactive elements can do that. This, in a sense, is the dream of the alchemists come true, even though the end products of all radioactive transformations—helium and lead—are far less valuable than the products from which we start, such as radium or polonium. At this stage I am less interested in the radioactive transformations themselves—I come back to these in Chapters XIX and XX—than in the alpha particles with which they supply the physicist. These alpha particles have enormous speed and are very small, so they are ideal for probing the inside of atoms.

In Chapter XV I try to tell you the exciting story of how Rutherford, using alpha particles as probes, discovered the atomic nucleus, and how this method can be used to measure its charge. From this it is only a step to the picture of electrons circling around the nucleus, and I shall try to show some of the difficulties involved in making such a

picture, and how they were overcome by Niels Bohr's surprising idea of providing the electrons with a limited selection of allowed orbits while forbidding all others. The question naturally arises, how do the electrons know which orbits are allowed?

Chapter XVI, which deals with this question, is easily the most difficult in the book. It begins by showing experimental evidence for L. de Broglie's discovery that a stream of material particles—for instance, electrons—shows wave properties as well, just as a beam of light waves has some of the properties of a stream of particles (photons), as described in Chapter XII. Once you accept this view I can show by a fairly simple argument that orbits which were forbidden in Bohr's model now are simply impossible, because no proper wave would fit them. This two-faced behavior of light and electrons—waves in some respects, particles in others—is a most peculiar and subtle affair and I have worked hard in trying to make it understandable. If you still don't understand it, perhaps it may be a consolation to you that very few physicists can claim to understand it fully, and that I am not one of them.

Chapter XVII should be a lot easier again. There I deal with some properties of atomic nuclei which indicate that they are made of protons (hydrogen nuclei) and neutrons. I shall tell you about the first experiment in which "an atom was split," that is, in which one nucleus was transformed into another by the impact of a nucleus. Told, too, is the exciting story of the discovery of the neutron.

Chapter XVIII is a description of the principal types of machines developed for splitting atoms. The cyclotron is the best known of them, but Van de Graaff's ingenious belt generator also gets a detailed description, and the betatron, which has a great future, is at least mentioned.

Chapter XIX brings up a very important subject, the equivalence of mass and energy. There I show how, from very accurate measurements of the weights of the nuclei taking part in a certain nuclear transformation, one can work out beforehand how much energy the transformation is going to liberate or consume. This chapter also contains some more about radioactivity and its explanation.

Chapter XX brings us pretty well to the limits of our present-day knowledge. It deals with such matters as the transformation of protons into neutrons and vice versa, the creation of positive and negative electrons out of radiation, and the possible existence of a particle, called the neutrino, which nobody has ever observed. This may sound a little confused and fantastic, but there are experimental facts—which I describe—at the bottom of it all.

Chapter XXI does not attempt to give a complete description of atomic power, how you produce it and what it can do; that would require a separate book. I have merely tried to show you briefly how atomic power fits into the pattern which I have unfolded in the preceding chapters, and what atomic power may be expected to do for us in the next few years.

ATOMS ON YOUR WATCH DIAL

FIRST OF ALL, I want to show you some atoms. Have you got a watch with a luminous dial, and a pocket magnifier? Then go into a dark room and wait a few minutes until your eyes are well accustomed to the darkness. Now look at your watch with the magnifier. You will see that the glow of the luminous stuff on the dial is not a quiet glow but a brilliant sparkle, a multitude of stars flashing and dying all the time. Each of these flashes is caused by the action of a single atom.

What is the stuff on the dial made of? The manufacturer will tell you that it consists mainly of zinc sulphide, with a trace of some copper salt, and some binding material. This mixture is phosphorescent, that is, if exposed to light it stores some of the light energy and emits it again as light, after a while. But gradually the stored energy is exhausted and after several hours in the dark the glow gets so weak that it can no longer be seen.

On some watches (in particular, cheap ones) the mixture I have just described is really all there is on the dial. These dials glow brightly immediately after exposure to light, but their brightness soon decreases; they show no sparkle under a magnifier, but merely a quiet glow.

What is it then that causes the sparkle on those other dials which glow all night? Let us ask the manufacturer again. He tells us that the luminous mixture on the "spar-

ling" dials contains, in addition to the phosphorescent zinc sulphide, a minute amount of a "radioactive" substance, usually radiothorium. The amount is so small that you will be surprised: it is of the order of a billionth of an ounce.

That sounds very little, but actually it is not very difficult to prepare such a small amount, and one does not need a delicate balance. Let us be scientific and start with one gram of some substance, say, ordinary salt. One gram is about $1/28$ of an ounce, or about half the weight of a dime; in Chapter X I shall give some reasons why physicists have chosen this weight unit in preference to the ounce or pound. We dissolve our gram of salt in a jug of water containing ten pints. After stirring well, we pour off nine pints and refill with water. You have now again ten pints of solution, but they contain only one-tenth of a gram of salt. If you pour off nine pints a second time and replace them by water, the amount of salt is reduced to one-hundredth of a gram. A third repetition gets you down to one-thousandth of a gram, commonly called a milligram. In this way you can go on in steps of ten, as far as you like. To get down to one hundred-millionth of a gram you need only eight such steps, and you can do that in a few minutes. Of course you would have to be sure that the water you use for refilling is completely free of salt, and that may be difficult.

This is perhaps a good place to introduce a way of writing very large or very small numbers which is used by scientists and saves a lot of time. Instead of writing a million as a "1" with six zeros behind it, we write 10^6 . Further, 10^3 means a "1" with three zeros behind it, or 1000. A billion is a thousand millions¹ and is usually written as a "1" and nine

¹ In America and France; in England and other countries it is a million millions.

zeros, so we write it 10^9 . You know the rule for multiplying large numbers, "add the number of zeros"; this rule is of course the same in our way of writing. So if you want to write a million billions, you have $10^6 \times 10^9$ which gives you 10^{15} because 6 and 9 are 15. On the other hand, if you divide you have to subtract the number of zeros. So if you want to divide a billion by a million, you have 10^9 divided by 10^6 which gives 10^3 , or a thousand, because 9 minus 6 is 3. Of course for numbers, say, below a million this way of writing is hardly worth while, but for larger figures it pays. Surely, 10^{17} is much quicker to write and to say (you say "ten to the seventeenth") than 100,000,000,000,000,000 or "a hundred million billions."

Whenever you divide by ten the exponent (the little number on top) drops by 1. A thousand, or 10^3 divided by ten gives 10^2 , or a hundred; if we divide again we get 10^1 , which is the same as 10. One more division gets us down to one, which we see may be written as 10^0 . Are we now stuck? Of course not; we can use negative numbers. One-tenth can be written as 10^{-1} , one-hundredth as 10^{-2} , one-thousandth as 10^{-3} (you say "ten to the minus third") and so on. One hundred-million-billionth is 1 divided by 10^{17} , which can be written as 10^{-17} , ten to the minus seventeenth. It may look unfamiliar to you, but it is not "mathematics," merely a more convenient way of writing very small numbers.

Twenty-four million can be written as 24×10^6 or 2.4×10^7 , whichever you prefer. If you want to multiply, say, 24 millions by 30,000, write $2.4 \times 10^7 \times 3 \times 10^4 = 2.4 \times 3 \times 10^7 \times 10^4 = 7.2 \times 10^{11}$. If you want to divide the same two numbers, 2.4×10^7 divided by 3×10^4 , you get 0.8×10^3 , or 800. How much is 600 divided by two billions? Now 6×10^2 divided by 2×10^9 gives you 3×10^{-7} , or three ten-millionths.

If you don't want to bother with the numbers in this book, you needn't; they are not essential for understanding the arguments. On the other hand, I think it would take you only half an hour's practice with examples like the ones just given to become sufficiently familiar with this type of reckoning to enable you to follow easily all the calculations in this book.

Let us go back to our watch dial. We said that the luminous stuff on it contains only about a billionth of an ounce of radiothorium. It is astounding what an enormous number of flashes is caused by this tiny amount. There must be thousands every second, and they keep flashing for years. And there is good evidence that each atom of radiothorium can cause only one flash.

Now if that is so, then the amount of radiothorium on your watch must gradually decrease since thousands of its atoms are "used up" every second. This is indeed the case. However, the flashes are so numerous that they are hard to count, and radiothorium has some confusing properties as you will see in Chapter XIX. So I propose we make a fresh start, using a more suitable radioactive substance called polonium, and arranging things so that we get a much smaller number of flashes every second.

We take a milligram of polonium, dissolve it in a drop of nitric acid (polonium is a metal and does not dissolve in water) and add water until we have one ounce. By a process of repeated diluting, as described before, we reduce the amount of polonium to 10^{-14} gram. Since we started with one milligram, that is 10^{-3} gram, we need 11 steps of dilution if each step gives a reduction by a factor 10 as before.

Next we take a few milligrams of powdered zinc sulphide (the accurate amount does not matter) and with the help of a drop of water and a toothpick we spread it upon a glass

plate so that it forms a reasonably uniform layer of perhaps a quarter of an inch in diameter. Then we put on our polonium solution, drop by drop, letting each drop dry before putting on the next one, in order to make sure that the solution does not spread all over the glass plate. When this is done we have a layer of zinc sulphide containing 10^{-14} gram of polonium.

We take this layer into a dark room and look at it with a magnifying lens. The amount of polonium was intentionally made so small that we do not get a brilliant sparkle but only an occasional light flash here and there. It takes considerable practice and concentration to count those light flashes, and you need a rest every few minutes. They come in irregular intervals, sometimes several in one second, sometimes none in several seconds. But if you count for a few hours you find that their rate is pretty constant, about 6000 per hour. Hence we must assume that our 10^{-14} gram of polonium is being used up at the rate of 6000 atoms every hour, 144,000 every day, or about a million a week.

This shows that 10^{-14} gram polonium must contain much more than a million atoms; after a week our sample is still flashing happily. However, if we count the flashes carefully, we find that their rate has indeed diminished during this week and is now down to 5800 per hour.

At this point I ought to stop and point out to you (like certain rather infuriating authors of detective fiction) that the necessary clues are in your possession to work out for yourself how many atoms are contained in a gram of polonium. The clues are these: In 10^{-14} gram of polonium, atoms get used up (that is, are transformed in such a way that they can no longer produce a light flash) at the rate

of a million a week; and after a week the rate of flashes is reduced from 6000 per hour to 5800 per hour.

Elementary, my dear Watson. If the rate of flashing has dropped by one-thirtieth (200 out of 6000), the reason must be that the number of flash-producing atoms has dropped by one thirtieth. Therefore the one million atoms which were used up during this week (clue number 1) must represent one-thirtieth of all the atoms present at the beginning; in other words, thirty million atoms must have been present at the beginning. This is then the number of atoms in 10^{-14} gram of polonium. One gram contains 10^{14} times as many, that is, $30 \times 10^6 \times 10^{14} = 30 \times 10^{20} = 3 \times 10^{21}$. So this is our answer: One gram of polonium contains 3×10^{21} atoms.

Measurements of this kind are actually somewhat more complicated, but my description contains all the essential features of this type of experiment; I have merely left out some details which would have obscured the main line of argument. For the same reason the numbers I used were round numbers. If I had used accurate numbers, the result would have been that the number of atoms in one gram of polonium equals 2.87×10^{21} . We shall soon see how this number can be compared with similar numbers obtained through entirely different methods. You will hear more about polonium in Chapters XIV and XIX.

III

CRYSTALS: ATOMS IN RANK AND FILE

Do you still have that pocket magnifier? Then shake a little table salt onto a plate and look at it. You will find that most grains are shaped like tiny cubes. If you dissolve some salt in water and let it evaporate slowly, you can get larger cubes, especially if you put a piece of string in the solution. As soon as some grains of salt have formed on the string, remove all but one. You can make this one grow to the size of a pea if you fill up with fresh solution every day. Kitchen soda is good stuff for growing large crystals. It dissolves more easily in hot water than in cold; if you make a saturated solution (that is, one in which no more soda will dissolve) in hot water and let it stand, once more with a piece of string for the crystals to form on, the solution will cool and no longer be able to hold all the soda, which then will come out in large crystals. Soda crystals are not cubes but have a more complicated shape. Unfortunately they do not keep in dry air.

Crystals are not merely regular in shape but have some sort of regular structure all the way through. You can cleave a moderately large salt crystal by applying a knife or chisel parallel to one of its edges and tapping it with a hammer. It will break into two halves with a shiny cleavage plane parallel to two of the original cube faces. Even if you just hit it with a hammer it will break into pieces which, though

irregular in shape, have all their facets parallel to the faces of the original cube.

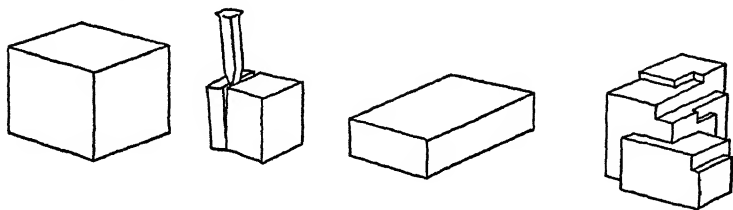


FIG. 1. A perfect crystal of sodium chloride (rock salt) has the shape of a cube; it can be cleaved (split) with a chisel; adjacent faces of a rock-salt crystal are at right angles, even if the piece has not the shape of a cube; even in an irregular fragment adjacent facets are at right angles, and opposite facets are parallel.

It is this internal structure rather than the external shape which characterizes a crystal. Some crystals found in nature have been ground into irregular shapes like pebbles, but their internal structure can be revealed by cleaving or in other ways. On the other hand, those dangling glass prisms which produce a festive sparkle on grandmother's chandelier are not crystals, in a scientific sense; they cannot be cleaved but break in an irregular shell-like fashion; other tests (which I shall explain presently) reveal no regular internal structure.

The fact that crystals can be cleaved is a pretty strong indication that they are made up of atoms, arranged in some regular fashion. If salt were completely homogeneous it would be very hard to understand why a crack produced by a knife or by a hammer blow should always spread along one of a few definite planes rather than follow the path of least resistance, as it does in glass. If, on the other hand, a crystal was something like a pile of bricks, held together by weak mortar, any incipient crack would naturally follow those already existing "planes of weakness."

Actually, we do not believe any longer that a salt crystal is like a pile of bricks. Nature has subtler ways of producing regular structures. If you want to understand these ways, go to a hardware store and buy a box (ten dozen or so) of small steel balls such as are used in bicycle bearings. Put the balls in a flat box large enough so that there are not enough balls to cover the bottom. First you hold the box level and shake it a little so that the balls are spread out; then you tilt it very slightly so that the balls tend to roll toward one corner. You will find that they arrange themselves into a regular pattern, looking somewhat like a beehive. If you drop another ball into the box it will automatically settle into such a position that it extends the regular pattern. If you add more and more balls they will eventually begin to form a second layer, interlocked with the first one and showing exactly the same pattern, and if you have a great many balls you can make a big pile with many layers, all interlocked and all perfectly regular.

By piling up balls in this fashion, you can get a perfect model of the arrangement of atoms in a crystal of kitchen salt (also called table salt, rock salt, or sodium chloride). The "beehive" layers do not run parallel to the cube faces, for their hexagonal pattern would clash with the rectangular shape of those faces, but rather across the corners; in other words, they are horizontal if the cube is made to balance on one of its corners. These details are not very important for what follows. If you are interested look at the drawing (Fig. 2) of a transparent hollow cube filled with steel balls, which gives you a pretty good idea of the arrangement of the atoms in a crystal of sodium chloride. Actually, sodium chloride contains two kinds of atoms in equal numbers, namely, sodium and chlorine atoms, arranged in alternate layers. You can see from the drawing that the intersection

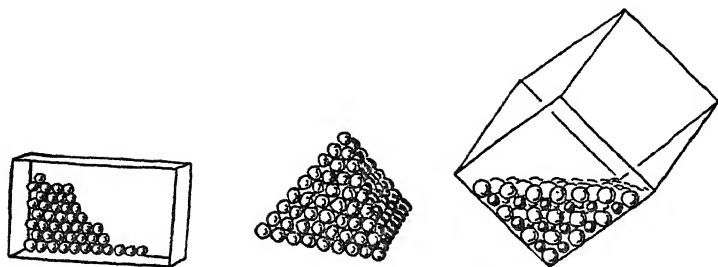


FIG. 2. Identical steel balls in a box arrange themselves in a beehive pattern; piled up in space they form a triangular pyramid (tetrahedron). In a similar way atoms and molecules arrange themselves to form crystals. Alternate layers of balls of two different sizes, placed in a cube which is balanced on one corner, represent accurately the arrangement of sodium and chlorine atoms in a rock-salt crystal.

of these layers with the cube faces produces a rectangular pattern looking like a chessboard.

What evidence have we physicists for such a detailed description? I shall try to show that we have very good evidence indeed. True, it is circumstantial and contains many bits of testimony not very convincing taken by themselves. But I hope when you have read it all you will admit the physicist's case is strong enough to be convincing.

The piece of evidence which comes closest to an eyewitness report is obtained by the use of X-rays. If a lead plate (say $1/8$ inch thick) with a $1/16$ inch hole in it is placed a few feet from an X-ray tube (such as the doctor uses to take a picture of your chest or to locate a bullet inside a soldier's body), the lead plate intercepts the X-rays except where the hole is. Thus, behind the lead plate we have a narrow beam of X-rays, which will produce a black spot on a photographic plate, placed a few inches behind the hole. If we cover the hole with a piece of window glass the X-rays are slightly weakened, but we still get a black spot on our plate, now surrounded by a halo of

blackening indicating that part of the X-rays were scattered on passing through the glass. However, if we replace the glass over the hole by a thin plate cleaved from a rock-salt crystal, we find something entirely different. Our original black spot is now surrounded with a striking, symmetrical pattern of additional spots of various degrees of blackness (see Fig. 3 and Plate 1).

The experiment I have just described was made for the first time (1912) by the German physicist M. von Laue who subsequently received the Nobel Prize. The symmetrical pattern of spots which he (together with Friedrichs and Knipping) observed for the first time is commonly called the "Laue pattern."

Why is this experiment so important that the man who did it received the Nobel Prize? The reason is that it achieved three important results: first, it established the wave nature of X-rays; second, it opened a way for analyzing X-ray spectra and measuring X-ray wave lengths with great accuracy (thereby creating a tool for probing deeply into the structure of atoms); and, lastly, it contained the germ of a method which now enables us to determine quickly and accurately the internal structure of the most complicated crystals.

You can see patterns somewhat similar to a Laue pattern if you look at a small, bright light source (for example, a distant street lamp) through a fine tissue such as a silk handkerchief or an umbrella. The threads in the tissue form two systems at right angles to each other, each system consisting of approximately parallel and equidistant threads. The holes between the threads thus form a regular pattern, not unlike the chessboard pattern of the atoms on the surface of a rock-salt crystal.

The pattern of colored spots which you see around a

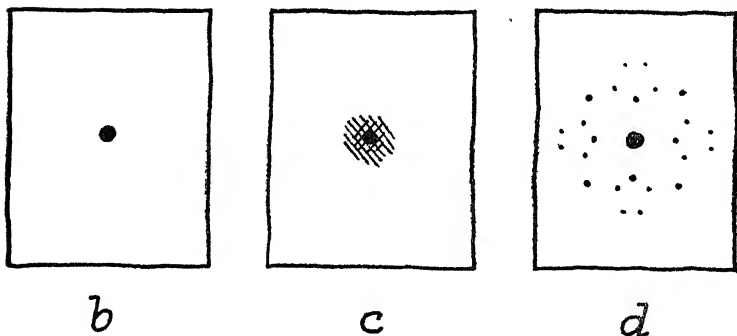
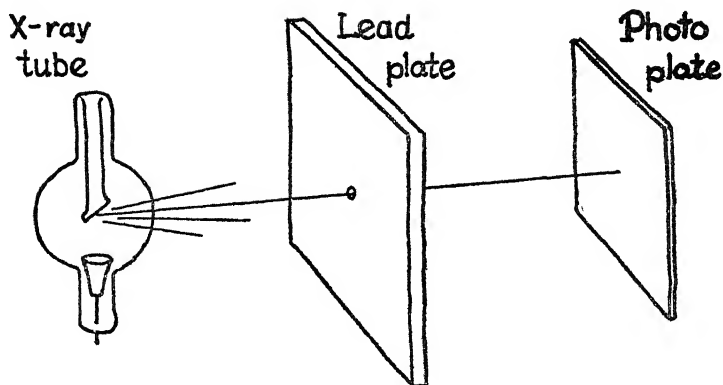


FIG. 3. A small hole in a lead plate allows a narrow beam of X-rays to go through; a photographic plate, exposed to this beam and then developed, shows a black spot (b). If a glass plate is placed over the hole the spot is surrounded by a diffuse halo (c); if, instead, a crystal (for instance of rock salt) is placed over the hole the spot becomes surrounded by a number of fainter spots, forming a symmetrical pattern, the shape of which depends on the arrangement of atoms in the crystal used (d).

street lamp if you look through a silk handkerchief is due to a phenomenon called "the diffraction of light," which I shall explain in the next chapter. The spots are usually somewhat blurred and fuzzy because of the irregularities of the silk threads. You can yourself produce "diffraction

screens" which are much more effective than a silk handkerchief in producing clear-cut and spectacular "diffraction patterns." All you need is a camera (a miniature camera is particularly well suited) and all you have to do is to take a picture of some object with a simple regular pattern, such as a window screen, a curtain, or wallpaper. Finely checkered fabric is admirable, so is a lacquered canvas suitcase. If you want to use a fabric, stretch it over a board or a door and fix it with thumbtacks, taking care the pattern remains straight.

The distance at which you place the camera affects the size of the image and is therefore important. The farther away you place the camera, the smaller will be the picture and the finer the pattern on it. It is desirable that the pattern be fine, but not so fine that the camera has trouble resolving it. A distance of about 0.1 mm ($4/1000$ inch) between neighboring dots or checkers, etc., on the picture is a good figure to start with. If the corresponding distance on the original fabric is, for instance, $1/4$ inch, you have to place your camera at such distance from the fabric that the image formed on the film is 60 times smaller than the original, that is, at a distance 60 times the focal length of the lens. If you use a miniature camera with a focal length of two inches (the focal length is usually engraved on the lens mount), you have to back up 120 inches = 10 feet from your fabric. After taking the picture, the film is processed in the usual way. Don't print it, just look through the film at a light source.

In Plate 2 you see several different screen patterns and the diffraction pattern which they produce. The real patterns are much prettier because they are colored; each of the dots (except the central one) is really a rainbow-colored dash. The diffraction patterns in Plate 2 were obtained with the

help of a colored glass which transmits only green light, thus reducing each of the rainbow-colored dashes to its green portion. If you study these diffraction patterns carefully (or even better, if you experiment with your own camera), you can soon discover and verify some simple rules which connect the appearance of the screen pattern with the appearance of the diffraction pattern it produces.

First, the two patterns have the same kind of symmetry. If the screen has a checkerboard pattern, which is built up of squares, the main diffraction spots form a rectangular cross. If the screen looks like a beehive, with dots arranged in hexagons, the diffraction pattern becomes a kind of star with six spikes. And if the screen consists merely of parallel straight lines, then the diffraction spots lie all on a single straight line through the central spot, a line perpendicular to the lines on the screen.

Secondly, as the screen pattern is made finer, the diffraction pattern becomes larger. If you back up your camera twice as much as at first, you get a screen pattern which is twice as fine. If you look at a light first through one and then the other, you will find that the diffraction patterns look exactly similar, only the finer screen gives a pattern twice as large as the coarser one. If you wish to compare the patterns accurately, look at one of those sodium lamps which give a bright yellow light (they are often used on highways and make people look like corpses). Using this you get not colored streaks but sharp dots like the ones in Plate 2. If you put the two films together and look through both of them at once, holding them so that their patterns are almost but not entirely parallel, you can see both diffraction patterns at once and you will find that one is indeed exactly twice as large as the other.

Thirdly, if the screen pattern is not quite sharp (for

instance, if the camera was not well focused) the diffraction pattern gets feebler; the outer spots tend to disappear.

You see that the symmetry, the size and the sharpness of a screen pattern are reflected in the diffraction pattern which it produces. In other words, if you are shown a certain screen pattern, you can predict with fair accuracy what the diffraction pattern will look like. And the reverse is true as well: from the appearance of the diffraction pattern you can draw fairly detailed conclusions about the screen pattern. If somebody gives you a screen which is so fine that you cannot recognize it with the naked eye, and if you have no magnifier or microscope which would allow you to see the screen pattern, you could still get a fairly good idea of what it is like by looking through it at a point of light and studying the diffraction pattern you see.

Now this is quite analogous to the way in which the physicist uses X-rays in order to study the structure of crystals. He has no microscope powerful enough to reveal the single atoms; but, by sending a beam of X-rays through his crystal, he gets a diffraction pattern which he studies in order to draw conclusions about the "screen pattern," that is, the pattern according to which the atoms are arranged.

From what I have said about the connection between screen patterns and diffraction patterns you may have received the impression that this connection is pretty vague, that it is based on experience and guesswork. That is not true. Mathematical methods exist which allow one to calculate the diffraction pattern accurately if the screen pattern is given, and vice versa. I have promised not to bother you with higher mathematics and I shall not try to explain those methods. But I shall try to explain the principal ideas on which these calculations are based, so as to give you at least a general notion of how it is done.

IV

ELECTROMAGNETIC WAVES

NEARLY EVERYTHING we know about the world around us we know through the evidence of our eyes. This trivial statement is doubly true for the atomic physicist, and much less trivial in his case. The astronomer, with the help of the telescope, has extended vision to distances beyond imagination; the microscope allows the biologist to see the finest detail of the living cell; but the "eyes" of the physicist cover a range of vibrations of which the colors of the rainbow—limits to our human vision—form but a narrow interval.¹ Before you know more about this range of vibrations—the electromagnetic waves—it would be useless to tell you much more about atoms. It would be almost like taking a blind man through a picture gallery.

We shall again begin with a simple experiment, for which we need a compass. There are elaborate and expensive compasses in which the magnetic needle floats in a liquid; this insures that, after being deflected, the needle quickly and smoothly returns to its equilibrium position. For our purposes I prefer a cheap compass in which, after a disturbance, the needle swings for a while and only gradually comes to rest. Sometimes the point on which the needle rests is blunt and the needle, after a few oscillations,

¹ The chemist stands outside this classification; he relies mostly on his nose. This remark is meant to express my deep respect for chemists, who have often drawn amazingly accurate conclusions from what—to a physicist—seemed very flimsy evidence.

comes to rest rather suddenly; such a compass won't do for us. For really good results you might take out the magnetic needle and suspend it by a very thin thread (or a hair) from the lid of a tall glass jar or milk bottle (to protect the needle from air currents).

If we bring a magnet near it the needle is deflected. One might say that the magnet acts on the needle through the intervening space; but the physicist prefers to express this a bit differently. In his parlance, the magnet creates a "magnetic field" all around itself; and the action of this magnetic field on the needle is what causes the deflection. This is merely a different way of describing the same fact, and apparently a more complicated one, but it actually has its merits. For instance, in some experiments the action of one or several magnets of complicated shape is brought to bear upon a piece of apparatus. In this case all one needs to know in order to understand the experiment is the magnetic field which acts on the apparatus, while the arrangement of magnets needed to produce such a field is arbitrary (within certain limits) and essentially an engineering problem.

The magnetic field generally varies from point to point and at any one point is completely described if one indicates the direction in which it points and its intensity. If a magnetic needle is left completely free to turn in every direction (also up and down) it will turn so as to indicate the direction of the magnetic field; the force with which it resists any attempt to twist it away from this direction is a measure of the magnetic field intensity. The field around a magnet has the greatest intensity near its poles and falls off rapidly with increasing distance from the magnet.

The fact that a compass needle points north is due to the

existence of a magnetic field which points north and is caused by the magnetism of the earth. If we bring up a magnet its own field becomes superimposed on the earth-magnetic field. The resultant field has in general a different direction and the needle obediently turns in this new direction.

This superposition of fields is a very important matter and I want to make it quite clear. If you bring up two magnets, each of which would produce, by itself, a certain field at a given point, the result is still just one field at this point. If the two fields are represented by two arrows indicating their respective directions, and if the lengths of the arrows are chosen so as to be proportional to the field intensities, one merely has to draw two more lines so as to get a parallelogram (see Fig. 4), and then the diagonal will be a representation of the resultant field.¹

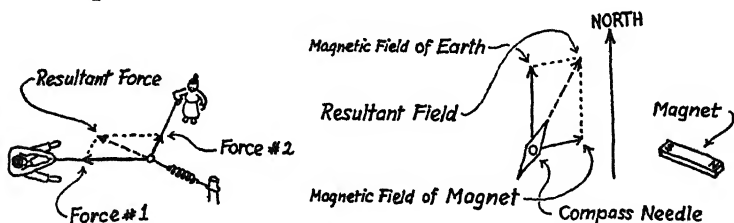


FIG. 4. If two forces act on the same body their combined effect—the resultant force—is found by the parallelogram construction shown. Magnetic fields combine according to the same rule, and a magnetic needle (compass needle) tends to assume the direction of the resultant field.

Two special cases of this superposition are of particular interest. If the two component fields point in the same direction, the resultant field has the same direction again and its intensity is the sum of the intensities of the two

¹ Forces, velocities and similar quantities which have a direction in space can be combined by the same parallelogram rule.

component fields. What happens if the two component fields have equal intensity but opposite directions? Answer: they cancel; the resultant field is zero.

Now back to our compass. We shall now use it to illustrate two very important concepts which will come up again and again in the course of this book, namely, resonance and interference.

If you bring a magnet close enough to the compass to produce a small deflection and then move the magnet away and back repeatedly at a slow rate, the needle will follow the motion of the magnet faithfully. If you take the magnet away suddenly, the needle will swing several times before coming to rest. Watch it carefully and note the rate (the "frequency") of these free oscillations. Now bring the magnet up again, to the same place as before, and again move it away and back repeatedly, but this time at the rate of the free oscillations of the needle. You will be able to produce much more vigorous movements of the needle than before, without moving the magnet by a greater amount. The oscillations of the needle are most vigorous if you hit the frequency just right; they become feebler if you move the magnet either faster or slower.

This is an example of resonance. If you like long words you can define resonance as "selective response of an oscillating system to a narrow range of frequencies." Examples from daily life are very numerous. In rocking a cradle or a rocking chair you make use of resonance by gently pushing in the proper rhythm. A child does this on a swing, a bell-ringer in church, and a man sometimes gets his car out of a ditch by rocking it back and forth. In music, oscillating systems play an important part, and so does resonance. If you press the "loud" pedal of a piano down (so that all strings can swing freely) and then sing a musical note you will

find that the piano continues to sound this same note after you have stopped singing it. This is because the string in the piano which is tuned to this note—and only this one string!—was set oscillating by the note you sang. In tuning a radio receiver to a particular station, you change the natural frequency of an oscillating circuit until it agrees with the frequency of the station you want to hear, in other words, until you have established resonance.¹

Now about interference. This is a very simple matter and really implicit in my earlier remark about the mutual cancellation of two fields of equal intensity and opposite direction. Let us try to set the compass needle swinging by using two magnets at the same time, and let us move the magnets in such a way that whenever one of them would turn the needle to the right the other would turn it just as much to the left. Obviously the needle remains at rest. Thus, while each magnet by itself would set the needle swinging, the two magnets “interfere” with one another so that the result is the same as if there were no moving magnets at all. In other words, two oscillating fields superimposed may have the same effect as no field at all.

Magnetic fields can also be produced with the help of electric currents, without using magnets. If you put a loop of wire not too far from your magnetic needle and then send a current through the wire with the help of a battery and a switch (see Fig. 5), you will see that the needle is deflected. If you reverse the current the needle gets deflected in the opposite direction. By reversing the current periodically you can make use of resonance and set your needle oscillating even if the loop of wire is some distance away (perhaps a foot or more). Such an arrangement is in

¹ With superheterodyne receivers the process of tuning is somewhat different but still depends on resonance.

principle a radio transmission system; the switch acts as the transmitter, the wire loop as the transmitting aerial, and the needle as the receiver. The currents used in radio change direction millions of times every second, and of

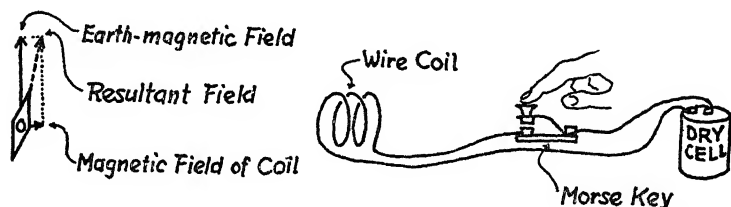


FIG. 5. An electric current sent through a wire coil produces a magnetic field similar to that of a magnet placed along the axis of the coil, capable of deflecting a compass needle. By repeatedly closing and opening the current in the right rhythm one can set the compass needle swinging vigorously, using the principle of resonance

course both the transmitter and the receiver are much more elaborate, but the principle is the same. In both cases we rely on the propagation of oscillating electromagnetic fields through the intervening space, in other words, on electromagnetic waves.

Now why do we call them "waves," and why do we call them "electromagnetic"? So far we have spoken only of magnetic fields, not of electric fields, which are the kind of field an electrically charged body creates around itself, just as a magnet creates a magnetic field. But the two kinds of field are not really independent. As long as a magnetic or electric field remains unchanged it can remain by itself; as soon as a magnetic field begins to change it creates an electric field, and vice versa. This mutual interaction is very hard to imagine clearly, but Clerk Maxwell, great Scottish physicist of the last century, calculated the effects of this interaction and found that it limited the speed with which any change in an electromagnetic field could spread through

space. And this speed limit for electromagnetic disturbances turned out to be 186,000 miles per second, the same as the speed of light. From this agreement Maxwell drew the conclusion that light itself consisted of electromagnetic waves, and many things were discovered since which entirely confirm this view.

We therefore can make magnetic fields or electric fields by themselves so long as we keep them constant, but when our field changes with time it is really always an electromagnetic field. If I move my magnet I create an electromagnetic disturbance which spreads through space with the speed of light. You may think that the needle responds immediately as I move the magnet, but actually a tiny interval elapses (one-billionth of a second if the magnet is one foot away) before the needle knows that the magnet has been moved. An electric charge has an electric field around it; but if you move it then it creates a magnetic field as well. An electric current is nothing but a stream of moving electric charges, and therefore it produces a magnetic field as already mentioned. In a transmitting aerial you have a current which alternately flows up and down, in a periodic way, and the electromagnetic disturbance which spreads to all sides is what makes radio possible.

Consider a radio transmitter operating on a frequency of one megacycle, that is, one million oscillations per second. If at a certain instant the current in the aerial is flowing upward it will do so again one-millionth of a second later, but in between, half a millionth of a second later, it will flow downward. In one-millionth of a second, light travels 300 meters, and so does the electromagnetic disturbance created by the oscillating current in our transmitting aerial. Hence, at the moment when the effect of a particular current maximum has reached a certain point, the effect of

the previous maximum has already reached a point 300 meters farther away, and the effects of still earlier maxima are being felt at points 600, 900, 1200, etc., meters farther away, while at intermediate points (that is, 150, 450, 750, etc., meters away) the fields have the opposite direction. The way in which the field varies with the distance from the source, at any one instant, is therefore represented by a wavy line (see Fig. 6) with a wave length of 300 meters (the wave length is the distance from one crest to the next). A ten-millionth of a second later the field will be represented by

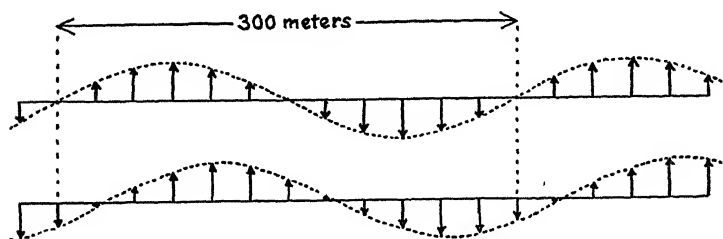


FIG. 6. A radio wave of 300 meters wave length. The transmitter is somewhere far to the left. Each arrow represents the intensity of the electromagnetic field at the point in question. The upper diagram refers to some particular time instant, the lower diagram to a time instant one ten-millionth of a second (10^{-7} sec) later.

a similar wavy line with all its crests 30 meters farther from the source. In other words, our fictitious wavy line travels away from the transmitting aerial with the velocity of light.

This is the reason for saying that the transmitting aerial sends out electromagnetic waves. While commonly accepted, this phraseology is somewhat loose in the sense that there is nothing really wave-shaped in the whole process, nor any wave motion as in water waves; but if you make a graphical representation of the way the field varies with the distance from the aerial, you get a wavy line. An electro-

magnetic wave is a periodic disturbance of the electromagnetic field, spreading through space with the speed of light. It is of course quite legitimate to visualize it with the help of a wavy line, provided you keep in mind that this is merely an aid to your imagination.

The description I have just given you is admittedly still quite vague. You might want to know exactly how the field intensity varies with time, how the electric and magnetic fields are linked and in which direction they point. However, I did not wish to burden you with all those details since they are not important for what follows. If you are interested to know, any textbook of optics will tell you.

V

THE COLORS OF THE RAINBOW

THE WAVES with a frequency of one megacycle and a wave length of 300 meters which I used for my example are ordinary radio waves. With the gradual improvement of radio engineering it became possible to attain higher and higher frequencies, that is, shorter and shorter wave lengths. Radar uses waves with lengths of only a few centimeters, that is, with a frequency of about ten billion (10^{10}) oscillations per second. Light waves are even shorter, less than one ten-thousandth of a centimeter (10^{-4} cm) in length. And ordinary X-rays have wave lengths which are still a thousand times smaller.

In order to measure the wave lengths of various kinds (colors) of light the physicist makes use of the interference of light waves. If light is an electromagnetic wave, then by suitably superimposing two light waves it is possible to achieve cancellation of their electromagnetic fields. In other words, it is possible to make an arrangement where light added to light produces darkness.

In Chapter III I described a way of making diffraction screens by photographing suitable regular patterns, and mentioned that a diffraction screen consisting simply of equidistant parallel lines gives a particularly simple diffraction pattern. Such a screen is called a diffraction grating, or simply a grating, and gratings belong to the most powerful research tools of atomic physicists.

Let us see if we can measure the wave length of "sodium light" with the help of one of our homemade gratings. We need a box, about a foot long—a shoe box will do. In one end we cut a hole, about one or two inches in size, and cover it with some translucent (not transparent) material such as tissue paper, oiled paper, or (best) matt glass. In the other end we cut a slit, say a sixteenth of an inch wide and an inch long. Now go some place where you can see one of those bright yellow street lamps (sodium lamps) and point your box at it, slit foremost. If you point correctly the light entering the slit will make a yellow line on your matt glass. Now you slide your diffraction grating over the slit, with its lines parallel to the slit. The yellow line will become feebler and additional lines (diffraction lines) will become visible on both sides of it. Next you must measure the distance between the central (original) line, and the diffraction line nearest to it. You can either hold a ruler against the screen and read off the distance between the two lines, or else mark their position with pencil on the matt glass and then measure the distance between the pencil marks at your leisure.

From the data now in your possession you can calculate the wave length of sodium light. Each of the transparent lines on your grating transmits a little fan of light; if you have only one transparent line (in other words, a narrow slit), you can actually observe it. With a grating, all those little fans of light interfere with one another and the result is mutual cancellation of their efforts, except in those few directions in which they cooperate. Now what does this cooperation mean? In Fig. 7 I have shown light rays which have been deflected by a certain angle on passing through the grating. Each ray is "ahead" of its lower neighbor by an amount indicated by a short thick line. Now if

this amount is just one wave length, then a wave crest¹ in one of the light beams at any particular time corresponds to a crest in the neighboring beam and so on all the way down the line. If you consider light beams deflected by a slightly greater angle, then the amount by which each beam is ahead

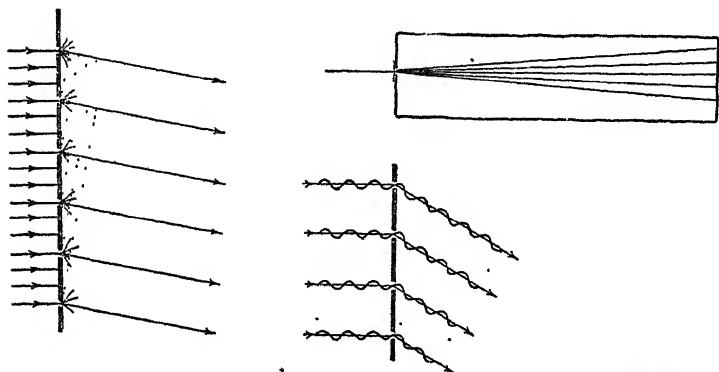


FIG 7. Diffraction of light on passing through a grating. Left: Light falls from the left on an idealized grating, an opaque plate with narrow slits, regularly spaced. A little fan of light emerges from each slit; the light beams marked with arrows have been drawn at an arbitrary angle to the incoming light, and the figure is meant to show that each beam is ahead of the next one by a fixed amount (the distance between dotted lines). If this amount is just one wave length all the beams cooperate to produce light (bottom right). Usually several diffracted beams are observed, on both sides of the undeflected beam (top right), corresponding to a shift of 1, 2, 3, etc., wave lengths between adjacent beams.

of its neighbor is also slightly greater; as you go down the row the waves get more and more out of step and the result is confusion, cancellation and hence, darkness. The directions in which light is actually observed must therefore be those in which each beam is just one wave length (or two, three, etc.) ahead of its neighbor.

¹ To be precise, a maximum of the electromagnetic field.

No doubt you now see how the wave length of sodium light can be calculated from your shoe-box experiment. If you take as a measure of the amount by which the light was deflected the ratio of the distance between your two pencil marks and the length of the shoe box, this ratio must be the same as the ratio between one wave length and the distance between two adjacent lines on your grating. Let us work out an example. If you use a grating with 30 lines per millimeter (762 lines per inch) and a shoe box of one foot (30.5 cm) length, the distance between the original yellow line on your matt glass and the nearest diffraction line will be 0.54 cm. The ratio indicating the deflection is $0.54/30.5 = 0.0177$. Hence the wave length must be 0.0177 times the distance between the lines of the grating. This distance is one-thirtieth of a millimeter or 3.33×10^{-3} cm; hence the wave length of sodium light is $0.0177 \times 3.33 \times 10^{-3}$ cm $= 5.9 \times 10^{-5}$ cm.

It is perhaps quite instructive to review the steps by which you have just measured a length of less than a thousandth of a millimeter, probably with an error not much greater than one hundred-thousandth of a millimeter, without ever using a measuring instrument more delicate than an ordinary ruler. First you measure the width of the stripes on the fabric which you photograph in order to make your diffraction grating. For this you can use a foot rule and just count how many stripes take up a space of one foot. Next you want to know by what factor the picture (the grating) is smaller than the original fabric. For this, as I indicated before, you merely need the focal length of the lens and the distance from the camera to the fabric; or else you can simply measure the width of the fabric both in reality and on the picture. This ratio is of the scale of 100 or 200, and if you divide the distance between strips

on the fabric by this number, you get the distance between adjacent lines on your grating, which is of the order of one-thousandth of an inch. To measure this distance directly would require some quite delicate instruments. From this to the wave length of sodium light is one more step, of about 60, the ratio of the length of your shoe box to the distance between the original line and the nearest diffraction line. The latter distance is only about one-quarter of an inch, but with a finely divided ruler it is not difficult to measure it without more than 2 or 3 per cent of error.

If you point your shoe box at a neon light you will see groups of red and yellow lines, in contrast to the single yellow line in the sodium light. In some places you find street lights which contain mercury vapor; they give an unpleasant bluish-green light and your diffraction grating reveals three prominent lines, a yellow, a green, and a blue one. An ordinary light bulb shows no diffraction lines but a rainbow-colored field in which the color changes gradually from red through yellow, green, and blue to violet. This sequence is called the visible spectrum. By making pencil marks at the appropriate points you can determine the approximate wave lengths corresponding to various colors. In this way you can ascertain that the visible spectrum comprises wave lengths from about 8×10^{-5} cm (red) to about 4×10^{-5} cm (violet). There are also waves of shorter length, called ultraviolet; they are easy to detect since they blacken the photographic plate just as visible rays do, and they are the ones which cause sunburn. The reason we do not see them is that they do not go through the lens in our eye.¹ Rays with a wave length of less than 2×10^{-5} cm cannot even go through air; but if you go to even shorter

¹ People who have had a lens removed—an operation undertaken to cure cataract—can see ultraviolet light; it looks violet to them.

waves, you eventually get to X-rays, of which I shall tell you in the next chapter.

There are also "infrared" rays, with wave lengths of over 8×10^{-5} cm. Photographic plates can be treated (sensitized) so as to be sensitive to infrared radiation up to about 10^{-4} cm wave length. Longer waves have to be detected by their heating effect and are for this reason sometimes called heat rays. This is somewhat misleading, for all electromagnetic waves produce heat when they are absorbed.

On the other hand, it is true that most of the heat radiated from a red-hot body is in the form of infrared rays. Why the photographic plate is insensitive to radiation above a certain wave length is a very interesting point to which I shall later come back.

Instead of separating lights of different colors with the help of a diffraction grating, you can use a glass prism. You may get one from an old chandelier, or buy it from army surplus stock. If you just look through it at an ordinary lamp bulb, the latter will seem to be quite strongly shifted from where it really is, and appear drawn out into a rainbow-colored streak. This is because the light rays get deflected in going through the glass¹ but rays of longer wave length (the red ones) are deflected less than those of shorter wave length (the blue ones). A sodium lamp will appear shifted but not drawn out because its light has all the same wave length. A mercury lamp will appear shifted and at the same time split into three images, yellow, green, and blue.

Prisms are used a great deal by physicists, usually in instruments which are called spectrographs. Figure 8 shows how such a spectrograph is constructed. It has a slit in

¹ This is called the *refraction* of light, in contrast to the *diffraction* which light suffers on going through a grating. The rainbow itself is a refraction phenomenon.

front, just like our shoe box; of course it is not made of cardboard but of accurately ground metal edges which can be pushed together with a screw, like the jaws of a little vise, so that the width of the slit can be adjusted at will. Next comes a lens, like that in a camera. This lens would produce an image of the slit, as indicated by the dotted

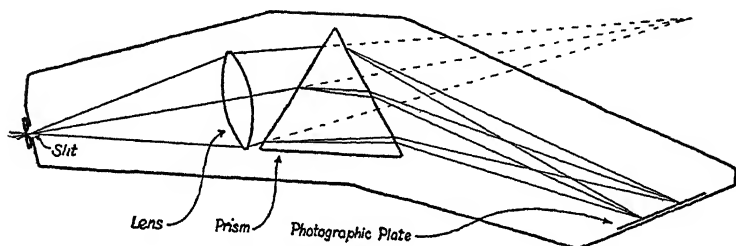


FIG. 8. A prism spectrograph, very sketchy. The light under investigation enters through the slit at the left; it is collected (focused) by the lens, turned sideways (refracted) by the prism (of glass or quartz) and recorded by the photographic plate. Light beams of two different colors (wave lengths) are represented; they strike the photographic plate in two different places, each producing a black line (an image of the slit) across the plate. A spectrograph commonly has two lenses (compare Fig. 16)

lines, if the light rays were not deflected by the prism. As a result of this deflection, the image is shifted and split up into as many images as there are different wave lengths in whatever light is made to enter the slit. This pattern of images is called the spectrum of the light; an ordinary lamp bulb gives a smooth rainbow-colored band, a "continuous spectrum," a neon or mercury lamp gives a "line spectrum," consisting of a number of separate lines, each of them an image of the slit. Usually the physicist places a photographic plate into this spectrum and then opens the shutter in front of the slit for a shorter or longer period (sometimes for hours if the light he wishes to study is weak), just as

in taking an ordinary photograph. Afterward the plate is developed and fixed in the usual way. The "spectral lines"¹ show up as fine black lines on the plate, and by measuring their distances and their degree of blackness one can find the wave lengths and the relative intensities of the different kinds of light emitted by the light source under investigation.

However, for very accurate measurements gratings are better than prisms. The gratings which are used for measuring the wave lengths of spectral lines are not made from photographic film like your homemade one. They are made by drawing lines with a diamond point on a polished metal plate. The diamond is guided so that it always follows the same straight line; the metal plate, after each line has been drawn, is moved a very small distance with the help of a very accurate screw. The first gratings of this kind were made by the American, H. Rowland, and some of the best existing gratings are his. You will realize what a ticklish job it is if I mention that some of these gratings have about 50,000 lines on a strip three inches wide, spaced with the utmost regularity.

There are only a few machines for making high-class gratings in the whole world, and their operation requires almost unbelievable precautions. The machine is suspended on springs and rubber cushions to prevent any outside vibrations from reaching it and operates entirely automatically in a room in which the temperature is kept constant to a small fraction of a degree. The screw, the most crucial part, has been ground and measured and reground for months by a first-class mechanic, to remove any traces of

¹Physicists have almost forgotten that "spectral" originally means "ghostly." But the early physicists who made the first rainbow-colored streaks with the help of glass prisms apparently thought it looked like a ghost, and since they wrote in Latin they called it "spectrum."

warp or skewness which would result in a grating with irregularly spaced lines. The metal plate is made of a special alloy (speculum metal) which takes and keeps a fine polish and is of uniform hardness, otherwise the diamond would not draw uniform lines. Many a promising grating was spoiled because the point of the diamond chipped in the middle of the process, and even if this does not happen the grooves may be too deep or too shallow for the best results. But if all goes well a research tool has come into being which may be decisive for the success of some school of physics or a research laboratory.

My friend, Dr. E. Rasmussen, probably won't mind if I show you his grating at the Institut for Teoretisk Fysik, in Copenhagen, Denmark. Mind the steps, we are going down into the basement. Has anybody a flashlight? It is hot in here because they keep the room at the same temperature the year round, and it is easier to heat a room than to cool it; also it keeps dry that way. You see some twenty stone pillars, about three feet high, standing in a circle of about twenty feet diameter. One of them carries the grating, a polished silvery-looking metal plate, about three by three inches in size and half an inch thick. It is held by screws in an upright position like a small toilet mirror, and if you stand in front of it you see the reflection of your face, slightly enlarged because the plate is slightly concave like a shaving mirror. The two rainbow-colored ghosts looking over your shoulders are merely your own diffraction images.

The grating faces toward the center of the circle of stone pillars and the pillar diametrically opposite the grating carries the "optical slit," formed by two finely ground vertical steel edges which, by the help of a screw, can be adjusted to form a fine slit of any desired width. Behind it there is a hole in the wall through which the light enters

which Dr. Rasmussen wants to investigate. On the other side of the wall is a laboratory in which various light sources can be set up.

Supported by the stone pillars is a circle of steel like a slender balustrade. It consists of two steel bands, one above the other with about half an inch between them. They define the surface on which the various diffracted rays come to a sharp focus. Photographic plates, made of specially thin glass, are bent slightly so as to fit snugly onto the curved steel bands, and are held in position by clamps. After an exposure which may last from a few seconds to several hours, the plate is developed and any spectral lines emitted by the light source show up as fine black lines across the plate. You can also clamp a thin matt glass plate onto the steel rails, in order to see the lines in their natural color. Those two fine yellow lines you see now, about an eighth of an inch apart, come from a sodium lamp behind the hole in the wall. Their wave lengths differ by only about one part in a thousand, and with a less powerful instrument (for instance your shoe-box "spectroscope") they appear as one line. Here they are widely separated, and a good grating has indeed no difficulty in separating lines which differ only by one part in twenty thousand in wave length (there are such lines!).

With instruments similar to the one we just saw, a great many physicists have put in a great deal of work. Each chemical element in gaseous form produces its own characteristic set of spectral lines if it is made to emit light either by electric discharge (as in the sodium, neon, and mercury lamps just mentioned) or by heating in a flame (a gas or spirit flame turns brilliantly yellow if you throw some kitchen salt into it because the kitchen salt—sodium chloride—contains sodium). This is very useful because any

unknown mixture or compound if vaporized and made to emit light will show the characteristic spectral lines of all the elements present, and this method of "spectral analysis" has gained great practical importance, for example, in the rapid analysis of metallic alloys. But even more important for us atomic physicists is the fact that those spectral lines represent the voice by which the individual atoms speak to us and by which they tell their secrets to the scientist who understands their language.

But I am straying too far from my immediate aim, which is to tell you how X-rays can be used to reveal the arrangement of atoms in crystals. This I shall do in the following chapter. Later I shall come back to spectral lines and shall try to show at least in outline how they can be used to elucidate the internal structure of individual atoms.

VI

X-RAYS

X-RAYS are made in X-ray tubes. An X-ray tube is an evacuated container (that is, one from which the air has been thoroughly pumped out) in which electrons are produced and directed toward a target which they hit at great speed. The target is a disc of metal, such as molybdenum, which is very heat-resistant; this is important since the electrons hitting the target rapidly lose their speed by collisions with the atoms in it and their energy of motion (their "kinetic energy") is converted into heat. In some tubes the target is cooled by water flowing through it, yet even then its surface gets fairly hot. In others the target is allowed to get red hot and then dissipate its energy as radiation (mostly infrared).

The X-rays are produced when the electrons hit the target and, curiously enough, they are produced in two entirely different ways. Some of the X-rays are caused by the rapid and irregular slowing-down of the electrons due to collisions with atoms; this irregular motion of the electrons produces irregular electromagnetic disturbances in which a wide variety of wave lengths is represented, somewhat like the continuous sequence of colors in the visible spectrum of an ordinary (incandescent) lamp bulb. The other way in which X-rays are produced in the target is when on occasion one of the intruding electrons jars the internal structure of a target atom, which then emits electromagnetic

radiation with a sharply defined wave length, rather like the spectral lines emitted from a neon lamp.

The diffraction of X-rays by crystals is a much more complicated phenomenon than the diffraction of light by a grating or even a diffraction screen. For a screen consists of a flat (two-dimensional) pattern while a crystal has a spatial, three-dimensional pattern; each layer of atoms in the crystal represents a plane pattern, and there are many layers. For this reason the type of arrangement which is suitable for a diffraction screen and which Laue used is rather difficult to interpret. I prefer to show you an experiment of the type devised by the late Sir William Bragg (see Fig. 9).

The apparatus consists, first of all, of an X-ray tube, and secondly of the X-ray spectrometer. The latter is a round flat box, perhaps six inches in diameter and one inch high.

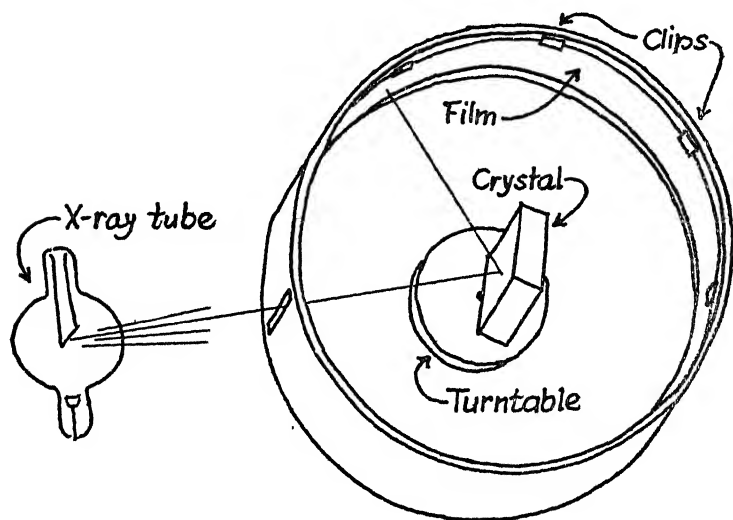


FIG. 9. X-ray spectrometer (Bragg's method).

At the point nearest to the X-ray tube the heavy metal wall has a slit through which a narrow beam of X-rays enters, aimed at the center of the box. There the beam is intercepted by a crystal mounted on a pivot. The cylindrical wall of the box is lined with a strip of photographic film wrapped in black paper; in this way the whole experiment can be done in daylight since the black paper does not stop the X-rays.

Now we switch on the X-ray tube and, at the same time, slowly turn the crystal. If the crystal were an ordinary mirror and if we were to use light instead of X-rays, the reflected light beam would slowly sweep over the film, and the film would get blackened uniformly. However, the X-rays behave differently. If we develop the film we find that there are some sharp black lines across the film which indicate that the crystal reflects X-rays practically only in certain sharply defined positions.

Now this is just what one has to expect if one pays due attention to the interference of the X-rays. In Fig. 10, the black dots represent atoms, the lines coming from the left represent X-rays striking the surface of the crystal at a certain angle, and the lines going to the right are reflected X-rays. Of course there are X-rays all over the place, and reflected X-rays are going off in a variety of directions; I have indicated only a few sample beams, for the sake of my argument. The wavy line along each beam is again merely a representation of how the electromagnetic field varies along each beam, at some particular instant.

Let us first consider the two top beams. They arrive with their wave crests abreast (else they would interfere with each other); then number 2 gets reflected and there follows a short period of confusion until number 1 has also been

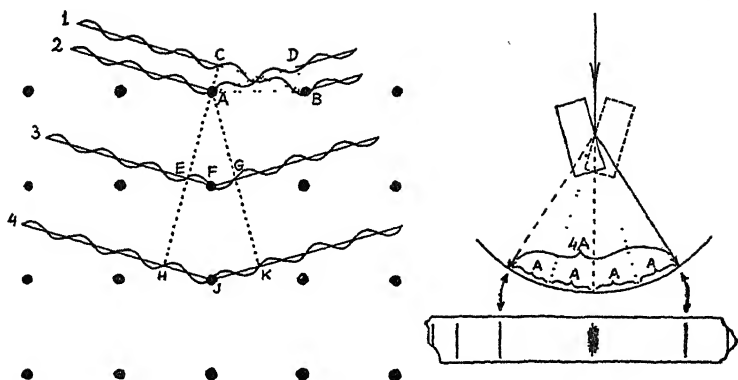


FIG. 10. The black dots represent atoms in a crystal. X-ray waves deflected (scattered) by some representative atoms (A, B, F, and J) are shown to cooperate if deflected by the angle shown. The drawing to the right shows the crystal in those two positions in which reflected beams occur to the left and right, respectively, and shows that the angle between these beams is four times the angle A, or four times the angle BAD in the left-hand drawing.

reflected. After that they run again side by side, with their waves in step as before. This is so because we have assumed that the beam makes the same angle with the surface before and after being reflected; hence the shaded triangles ABC and BAD are congruent and the paths CB and AD of the beams during the "period of confusion" are equal.

If, on the other hand, we compare beams 2 and 3 we see that beam 3 gets reflected later and has to travel an extra distance before it is again abreast of beam 2. If the distance EFG by which beam 3 after reflection is behind beam 2 is just one wave length, then the two beams will be again in step after reflection. The same will be the case with beams 2 and 4 because number 4 will be just two wave lengths behind number 2, and, likewise, all the beams reflected by even deeper layers of the crystal will emerge with their waves all in step.

All this is true only if the distance EFG is just equal to one wave length (or to two, three, or any whole number of wave lengths), and that is the case only for certain definite angles. If the angle is wrong, then the waves will get more and more out of step as we consider beams reflected by deeper and deeper layers. Then, instead of cooperating, the various beams will interfere with one another and hence X-rays striking the crystal at a wrong angle will not be reflected. The whole argument—as you will have noticed—is very similar to the argument by which, on page 36, I tried to explain the diffraction of light by a grating.

For those of you who like to see exactly how these things are done I shall describe an experiment step by step and show the whole calculation so that you may see how the final result is obtained. You can skip over the details if you are not interested; they contain nothing which is needed to understand the rest of the book.

We use a special X-ray tube in which the target is made of copper. A thin foil of nickel, placed between the tube and the spectrometer, helps by absorbing most of the characteristic X-ray lines of the copper target, leaving only one, which has a wave length of 1.54×10^{-8} cm. The X-ray tube is adjusted until the beam which enters through the slit goes right through the center of the spectrometer.¹ This can be done by mounting a piece of photographic film on the pivoted table at the center; you switch the X-ray tube on for a minute, develop the film and see if the black line which indicates where the X-ray beam has struck is in the middle of the film. If not, you shift the X-ray tube slightly,

¹ This need not be done very accurately since it can be shown by elementary geometry that the beam which is reflected at the correct angle (the angle permitted by the interference of the X-rays) always strikes the photographic film in the same place, even if the X-ray tube is shifted slightly.

and repeat the procedure until the adjustment is completed.

Next we take a rock-salt crystal with a nice cleavage plane and mount it on the pivoted table with a trace of wax, with its cleavage plane upright and the lower edge of the cleavage plane passing through the center of the table. With the help of a magnifying glass this adjustment can easily be made to a fraction of a millimeter.

The inner wall of the spectrometer forms a smooth circular (or rather cylindrical) surface with a radius of exactly 5 cm. The circumference of the circle is therefore $2\pi \times 5 \text{ cm} = 31.4 \text{ cm}$ (π is the ratio between the circumference of any circle and its diameter and is 3.14159...). We don't want to block the slit through which the X-rays enter; so we cut out a strip of film a little shorter than the circumference of the spectrometer, say 30 cm long (a little under one foot), wrap it in black paper, seal it with scotch tape and insert it in the spectrograph. There are little springy clips to grip the edges of the film and make it lie snugly against the cylindrical wall all the way around.

The pivoted table is connected to a clockwork which when set going will very slowly turn it around. Before doing this we turn the table so that the X-ray beam just grazes the cleavage face of the crystal. Make sure the direction is right so that when we switch on the clockwork the cleavage plane will gradually turn toward the slit (and not away from it). All set? You switch on the X-ray tube while I set the clockwork going. Now we have an hour's time since it takes the clockwork that long to turn the crystal around.

Those X-rays are really marvelous tools in many ways. You know of course that they go right through the human body, although they are weakened somewhat, particularly where they have to go through bone. Certain chemical compounds (similar to the stuff on your luminous watch

dial) emit light when struck by X-rays. If you hold a screen painted with such a "fluorescent" substance near an X-ray tube the screen glows with greenish light. If you hold your hand between the tube and the screen the shadow of your hand appears on it, or rather the shadow of the bones in your hand while the flesh and skin are only faintly visible. Doctors use this arrangement to see where a bone is broken, or to locate metal fragments or bullets. The fluorescent screen may be replaced by a large piece of photographic film; an exposure of a few seconds suffices to get a good picture which the doctor can study at his leisure.

X-rays can also be used in the treatment of disease, especially cancer; on the other hand they can cause disease and even death if the body gets too big a dose of them. In the early days of X-ray science a number of doctors fell victims to the force they had not learned to tame. Nowadays we have accurate instruments for measuring the dose of X-rays received by any doctor, nurse, or patient, and with reasonable care there is no danger in X-rays any more.

Another interesting and important property of X-rays is that they make air and other gases electrically conducting while they pass through them. The electric currents which you can get to flow through air under the influence of X-rays are very small, millions of times smaller than the current needed to light a lamp bulb, but instruments for measuring very small currents have been available for many years and are constantly being improved. With their help you can measure the intensity of X-rays which are so weak that it would take them days to blacken a photographic plate.

How long has our experiment been running? Half an hour? Let us go back and see if everything is as it should be. Yes, the power supply for the X-ray tube is still hum-

ming quietly and the filament in the tube is still glowing. The charwoman has not removed the spectrometer in order to dust underneath (these things happen, you know). The crystal has turned by 90 degrees and its cleavage plane is now facing the slit as it should, and the clockwork is still ticking. All right, we can leave it for another half hour.

You have probably heard the terms "soft" and "hard" X-rays. This is merely a different way of indicating the wave length. Long-waved X-rays are soft, that is, they have little penetrating power. Those X-rays which our copper target just now is sending into our spectrometer will penetrate a sheet of paper, but a piece of heavy cardboard will weaken them appreciably and a human hand will stop them. Hence they are no use in medicine, except when a doctor wants to irradiate the skin without affecting the tissues below. There are still softer X-rays which have trouble even in penetrating ordinary air; to study these the physicist has to pump out the air from his entire apparatus so that the X-rays can proceed unhindered. If you experiment with longer and longer waves you find yourself at last dealing with rays which we earlier called ultraviolet. The whole transition region has been experimentally explored and while the properties of radiation change profoundly within this region we must realize that these changes are gradual and that there is no difference in kind between X-rays and visible light.

On the other hand, if you make the wave length shorter the X-rays get harder. Hard X-rays are useful through their power of penetrating thick steel plates and castings, making internal flaws visible; they are also used in medicine when the doctor wants to irradiate some deep-seated tumor without damaging the tissues above it. In order to produce harder X-rays one has to increase the speed of the electrons

which strike the target. This is done by increasing the electric potential which drives the electrons toward the target, and while our little X-ray tube (how is the time getting on, five minutes yet?) runs peacefully on about ten thousand volts, huge X-ray tubes have been built in which the electrons are hurled toward the target by a potential of two million volts or more. Recently a new instrument has been developed, the betatron, in which, without the use of high potentials, electrons can be brought up to the same speed as if accelerated by a potential of twenty million volts. The X-rays which this machine produces can go through several feet of solid steel. And this is not the end: while I am writing this the General Electric Company announces the successful operation of a betatron for hundred-million-volt X-rays.

We are just in time; the crystal has turned by 180 degrees and the X-rays are once more skimming its surface. Now we can switch off the tube, stop the clockwork and take out the film. It has to be developed, fixed, washed, and dried; this is photographic routine and I see no point in describing it to you.

Here is the finished film (see Fig. 10). It is slightly fogged all over, partly from the continuous X-ray spectrum mentioned before which comes from the irregular motion of the intruding electrons in the target. In the middle there is a heavy black line across the film, smudged and irregular; this is caused by those X-rays which missed the crystal at the beginning and at the end of the exposure when the cleavage plane was nearly parallel to the beam and did not intercept all of it.

To the left and right of the heavy line there is about an inch of clear space and then comes a sharp black line on each side. These two lines are the traces of those X-rays

which were reflected from the cleavage plane of the crystal in the way explained before. By putting a millimeter scale on the film we find that the two lines are 55 mm or 5.5 cm apart. During the exposure the film was bent to form a circle of 4.95 cm radius (I have subtracted half a millimeter from the radius—5 cm—of the spectrometer in order to allow for the thickness of the black paper behind the film and that of the film itself) and the circumference of this circle is $2\pi \times 4.95 \text{ cm} = 31.1 \text{ cm}$. Since a full circle is divided in 360 degrees, we have to divide the 31.1 cm by 360 in order to get the length of one degree of the film, which we find to be .0863 cm. The distance of 5.5 cm between the two lines on our film corresponds therefore to an angle of 5.5 divided by .0863 = 63.7 degrees.

The diagram (right half of Fig. 10) shows how this angle is connected with the angle between beam and crystal surface for which the X-ray interference allows reflection to occur. If the latter angle is called A , and remembering that the angle between the crystal surface and the reflected beam is again A , you will have no difficulty in finding that the angle between the two reflected beams is four times A . Hence A is one quarter of 63.7 degrees or about 15.9 degrees.

The diagram on page 49 was drawn in such a way that the angle between the incoming beam and the crystal is 15.9 degrees; hence the diagram accurately represents the reflection of the X-rays in our experiment. Therefore the angle ABC is 15.9 degrees and so is the angle EAF . Now EF is just half the wave length of the X-rays while AF is the distance between atomic layers in the rock salt we are trying to measure, and AEF was drawn a right angle. If you know trigonometry you will simply say, AF is EF divided by the sine of 15.9 degrees; you look up $\sin 15.9^\circ$ in a trigonomet-

ric table and find that it is 0.274. Or else you can draw the triangle AEF on a large scale on a piece of paper, making the angle AEF accurately 15.9 degrees with the help of a protractor; then measure the sides EF and AF and divide the first by the second. If you do it accurately you should again get 0.274. Since we used X-rays with a wave length of 1.54×10^{-8} cm, EF is one-half of that or 0.77×10^{-8} cm. Consequently, AF is 0.77×10^{-8} cm divided by 0.274 which gives 2.81×10^{-8} cm.

This is then our answer: The distance between those atomic layers in a rock-salt crystal which run parallel to the crystal faces is 2.81×10^{-8} cm. If the atoms were little hard spheres packed together like the steel balls in our model, each of these little spheres would have a diameter of 2.81×10^{-8} cm. It is now easy to calculate how many atoms there are in a cubic centimeter of rock salt. A cubic centimeter is the volume of a cube with sides one centimeter long. Along one side the number of atoms in a single row is 1 divided by 2.81×10^{-8} , which is 0.356×10^8 , or 3.56×10^7 , or 35.6 millions, whichever you like best. In one layer there are 35.6 millions of these rows, or $3.56 \times 10^7 \times 3.56 \times 10^7 = 12.67 \times 10^{14}$ atoms. In our cubic centimeter there are again 35.6 millions of these layers and hence the total number of atoms in it is $3.56 \times 10^7 \times 12.67 \times 10^{14} = 45.3 \times 10^{21}$ or 4.53×10^{22} atoms. Later, in Chapter VIII, I shall show how this number may be compared with the number of atoms in a gram of polonium which we determined in the first chapter. But first let me say a few more things which concern X-rays, and answer a few questions which might have occurred to you.

VII

MORE ABOUT X-RAYS

ONE QUESTION you may have been wanting to ask me is: How does one know the wave length of X-rays? The measurement of the distance between atoms in rock salt was based on the fact that a certain kind of X-rays has a wave length of 1.54×10^{-8} cm. How has this been measured? Well, this again was done with the help of gratings, in essentially the same way you measured the wave length of sodium light with your shoe-box spectrometer. The gratings used are ruled on polished metal as described previously. There are two difficulties in using gratings for X-rays. One is that due to their great penetrating power X-rays are very feebly reflected from metal plates. The other difficulty is that because of their short wave length (more than a thousand times shorter than that of visible light) X-rays give diffraction patterns which are clustered very closely around the central beam and therefore very hard to resolve.

Fortunately, both difficulties can be overcome by one and the same trick, namely, by letting the X-rays strike the grating at an almost glancing angle. The reflection of X-rays by metal plates becomes more pronounced as the angle between the beam and the metal surface is decreased. At angles below one degree a sufficient part of the X-rays is diffracted to form a trace on a photographic plate; if lines have been ruled to turn it into a grating, diffraction

spectra will appear as well, and become more and more spread out as the angle is made more nearly glancing. From the angles between the metal surface and both the reflected beam and the diffracted beam nearest to it, the wave length can be computed by an argument similar to the one used earlier, although a bit more complicated because of the oblique incidence.

You may further ask how we deduce the accurate arrangement of the atoms. The experiment I described tells us only that they are arranged in layers parallel to the cleavage plane, with a spacing of 2.81×10^{-8} cm. True, but you must remember that there are three sets of cleavage planes in a rock-salt crystal, at right angles to each other, and that they all show exactly the same behavior with respect to X-ray reflection. Hence we know that the atoms lie on three systems of parallel planes which intersect each other at right angles. There are only a few regular arrangements which fulfill this condition. Furthermore, there are other layers of atoms in the crystal, for instance, the "beehive layers" across the corners. They, too, will reflect X-rays at certain angles and in this way we can make sure they are there and measure their spacing. On our film there are many more lines (see Fig. 10) which we ignored: these are the traces of X-rays reflected by some of those other planes. With a few measurements of this type we can quickly eliminate all possible atomic arrangements but one, which must then be the true one.

By methods more or less like these, a great many physicists have done a great deal of work in determining the arrangement of atoms in all the common crystals and many uncommon ones. The variety they found is even greater than the already bewildering variety of crystal shapes; for instance, cesium chloride which is chemically

akin to sodium chloride (rock salt) and likewise crystallizes in cubes has its atoms arranged in a different way. It was discovered that some crystals change the arrangement of their atoms when heated above a certain temperature, without changing shape. To mention only one practical application, the heat treatment of metals (as, for instance, the hardening of steel) has become a science rather than an art, thanks largely to the detailed information on the crystal structure of metals which X-ray diffraction has given us.

From a practical point of view, the investigation of crystals with the help of X-rays is of the greatest importance; to the atomic physicist the investigation of X-rays with the help of crystals is perhaps even more interesting. The measurement of X-ray wave lengths by means of ruled gratings is very laborious because of the low intensity of the reflected and refracted beams and the small angle between them. Once the spacing of atomic layers in a certain crystal has been established with sufficient accuracy it is much more convenient to use this crystal for the measurement of X-ray wave lengths.

At the beginning of the chapter I mentioned the characteristic X-ray lines which are emitted by the target of the tube and which are due to the jarring of the target atoms by the impinging electrons. In our experiment we deliberately absorbed part of the characteristic X-rays of our copper target by means of a thin nickel foil; if we omit this nickel foil we find three X-ray lines fairly close together and a few others farther away. If we replace the copper target in our tube by a zinc target¹ we get a similar group of three lines, slightly shifted toward shorter wave lengths. If you use other elements for a target you always get such a group of

¹ The X-ray tubes used for this kind of investigation are made so that they can easily be dismantled and reassembled.

three lines, but no two elements have it at the same place on the wave-length scale.

The wave lengths of these lines have been measured for a large number of elements and it was found that one can arrange all these elements in such a way that the wave length of any one of these three lines decreases regularly from one element to the next. This arrangement of elements is the same as that gotten by arranging the elements in the order of increasing atomic weight.¹ The regularity with which the wave length changes from one element to the next is so great that it even led to the discovery of a new element. It was noticed that from lutecium to tantalum—the next heavier element known at the time—the wave length changed by twice as much as between other neighboring elements of similar atomic weight as, for instance, between tantalum and tungsten. Chemists searched for a suspected missing element in vain. The discovery came only after greater insight into the structure of atoms allowed a better prediction of the chemical character of the missing element. Niels Bohr made the prediction and De Coster and Hevesy isolated the element in Copenhagen and—after Copenhagen's old Latin name—called it hafnium.

There is a striking contrast between the regular behavior of the characteristic X-ray lines and the haphazard appearance of the visible spectral lines of the elements. Neon shows a number of red and yellow lines while its neighbor sodium has only one yellow line (or two very close together, to be precise). Iron, which is heavier, gives several thousand visible lines while mercury, which is still heavier, has only three strong and a few weaker ones. Later, in discussing the

¹ There are a few discrepancies between the two arrangements, which we shall explain later.

internal structure of atoms, we shall return to these facts and show how they fit in.

The continuous X-ray spectrum, the one which is caused by the irregular motion of the intruding electrons in the target material, also has some interesting features. I said before that one has to hit the target with electrons of greater speed in order to produce harder X-rays, that is, ones of shorter wave length. In a qualitative way, this is not so difficult to understand. Faster electrons make more violent collisions; more violent collisions mean more sudden changes of speed; more sudden change of speed means more rapid change in the electromagnetic field; this means the appearance of oscillations of higher frequency in the X-ray spectrum; higher frequency means shorter wave length. It is not very difficult to translate this argument into mathematical language and to predict the way in which the intensity of the continuous X-ray spectrum should fall off toward shorter wave lengths, for any given speed of the impinging electrons.

I said "should fall off," for in reality the intensity does not fall off in the gradual way predicted by the foregoing argument. In reality the intensity falls to zero at a certain wave length and no shorter waves can be detected with the most sensitive instruments. This "short-wave limit" does not depend on the material of the target. It depends only on the speed of the electrons, and in a very simple fashion the limiting wave length is inversely proportional to the kinetic energy of the impinging electrons. If you double the kinetic energy of the electrons (by doubling the voltage used to hurl them against the target), the limiting wave length is halved. Or, to put it differently: the highest frequency you can get is proportional to the kinetic

energy of the electrons. It seems that X-rays of higher frequency are more valuable since you have to use electrons of higher energy in order to get them. And their value is firmly established and not subject to any bargaining; if you want to make X-rays of a certain frequency you must use electrons of the appropriate energy or more, otherwise no business.

I wish to impress upon you that the existence of this short-wave limit is an experimentally established fact, and if it disagrees with some preconceived ideas about the production of X-rays by moving electrons it is those ideas which have to go. Nor is it an isolated fact; there are many others—some of them I shall discuss later in the book—which point in the same direction and which forced upon us the great revolution in physical thought which is symbolized by the term “quantum theory,” a revolution which started in 1900 and is, in a sense, still going on.

VIII

HOW MUCH DO ATOMS WEIGH?

LET US go back a bit. We have two results concerning the number of atoms in a given amount of matter, obtained by entirely different methods. One result is that a gram of polonium contains 2.89×10^{21} atoms of polonium, the other is that one cubic centimeter of rock salt contains 4.53×10^{22} atoms, half of them being sodium, the other half chlorine atoms. Is there any way of relating these two results?

There is, and for this we have to call in the chemist. Indeed, a lot was known about atoms, thanks to the results of chemistry, long before physicists even believed that atoms existed. I shall try to recapitulate the relevant facts fairly quickly because they have all been known for a long time and quite likely you know all about them.

Some substances are called chemical compounds; they can be decomposed by heat, electric current, or the action of other chemicals. The decomposition products may still be compounds, in turn capable of being decomposed; but by repeating this process one eventually comes to substances which can no longer be decomposed and which are called elements. If sugar is heated in the absence of air it chars, and steam is given off. The black residue is carbon, an element. The steam can be condensed to water, which can again be decomposed—for instance, by an electric current—into the two gases, hydrogen and oxygen, both ele-

ments. Hence sugar is a chemical compound of the elements carbon, hydrogen, and oxygen.

You can grind up the charred residue and mix it with the water that was driven off; you will get a black dough but not sugar. A chemical compound is not just a mixture of the elements it contains. One important difference is this: while you can prepare mixtures containing more or less water and the same amount of carbon, the proportion of carbon and water which you get by decomposing sugar is always the same. And water contains always eight times as much oxygen (by weight) as hydrogen.

An important part of the work of chemists has been to find in what proportions the various elements combine to form chemical compounds. These proportions are by no means constant. Slaked lime contains oxygen and hydrogen just as sugar does, but it contains not eight but sixteen times as much oxygen. If copper is heated with a certain amount of oxygen it forms a bright red compound; if the amount of oxygen is doubled a black compound results. From innumerable experiments of this kind the atomic theory of chemistry grew up, the principles of which we can formulate as follows:

Each pure chemical compound consists of molecules which are all alike.

Each molecule consists of two or more kinds of atoms.

An element consists of atoms which are all alike, and which cannot be further decomposed.

To a large extent these statements were confirmed by the physicists when they developed methods for checking them. Many assertions of chemists regarding the structure and shape of molecules turned out to be accurate to a degree that was positively uncanny. Whenever I tend to get con-

ceited about some successful prediction made by an atomic physicist I regain a becoming degree of humility by remembering how the chemist Kekulé, on purely chemical evidence, asserted that the benzene molecule contained six carbon atoms arranged in a hexagon, and how it took the physicists about forty years before they found independent evidence that he was right.

Slaked lime contains equal numbers of oxygen and hydrogen atoms, hence the oxygen atom must be sixteen times as heavy as hydrogen. In a water molecule, two atoms of hydrogen are attached to one oxygen atom; that explains why in water there is only eight (and not sixteen) times as much oxygen as hydrogen. It is important to point out that from purely chemical experiments one can never obtain the true weight of an atom but only the weight ratio between two kinds of atoms. Since the hydrogen atom was found to be the lightest of all, the chemists decided to use its weight as a unit with which to express the weight of other atoms. They say "oxygen has the atomic weight 16" and mean thereby that an oxygen atom is sixteen times as heavy as a hydrogen atom. In other words, the atomic weight of an element is the weight of one of its atoms divided by the weight of a hydrogen atom. We also speak of the molecular weight of a chemical compound, which means the weight of one of its molecules relative to the weight of one hydrogen atom.

Now let us return to the fact that one cubic centimeter of sodium chloride contains 4.53×10^{22} atoms. The chemist tells us that sodium and chlorine have atomic weights of 23 and 35.5 respectively, hence the molecular weight of sodium chloride is $23 + 35.5 = 58.5$. One cubic centimeter of sodium chloride weighs 2.15 grams, hence one gram contains 4.53×10^{22} divided by 2.15, or 2.11×10^{22}

atoms, or half as many molecules, that is 1.055×10^{22} sodium chloride molecules. Therefore each of these molecules weighs one gram divided by 1.055×10^{22} , or $.945 \times 10^{-22}$ gram. Since the molecular weight of sodium chloride is 58.5, one atom of hydrogen weighs 58.5 times less than a molecule of sodium chloride, or $.945 \times 10^{-22}$ gram divided by 58.5, which is 1.62×10^{-24} gram.

We have beaten the chemists! We have determined the real weight of a single hydrogen atom, and from it we can now calculate the weight of any atom or molecule we like. But can we be really sure that our result is correct? We have used a complicated and indirect method, based on rather subtle arguments, to find the number of atoms in a cubic centimeter of sodium chloride; have we perhaps made a mistake somewhere? Is there any way to check our result?

Of course there is. We have found, by an entirely different method, that there are 2.89×10^{21} atoms in a gram of polonium, hence one atom of polonium weighs 3.46×10^{-22} gram. The chemist tells us that the atomic weight of polonium is 210. If we divide 3.46×10^{-22} gram by 210 we get another answer to the question, "How much does a hydrogen atom weigh?" and this time the answer is 1.65×10^{-24} gram.

The two answers, obtained by independent methods, differ by 2 per cent only. Such good agreement can hardly be fortuitous, and unless the same error should have crept into both our methods—which seems unlikely since they use quite different types of arguments as well as different materials—we can only conclude that both methods are correct. The 2 per cent difference comes partly from the fact that no measurement is ever completely accurate, partly from the careless fashion in which I have carried

out the calculations, using two decimals only. With appropriate care much better agreement is found.

Let me dwell a little on this matter of checking results. Unless a method has proved its reliability many times, the physicist never relies on a single measurement. At the very least he repeats the same measurement several times to see by how much the result fluctuates; usually he varies the conditions of the experiment in order to make sure that they don't affect the result. If it is a matter of measuring a "fundamental constant," such as the weight of an atom of hydrogen, he is not satisfied until he has measured the same quantity by several completely independent methods and found the same answer every time. This caution is necessary in a field in which most of the evidence is highly indirect. On the other hand, if a number of checks have been made with satisfactory results, the physicist can feel a high degree of confidence in his work, and, in my opinion, the weight of an atom of hydrogen is as well known as if weighed on a pair of scales. The two methods which I have discussed at some length are only two examples out of a large number; later I shall describe a third one and briefly indicate others.

Molecules are of very different sizes. A sodium chloride molecule contains two atoms, a water molecule three, but a sugar molecule contains forty-five (twelve carbon, twenty-two hydrogen and eleven oxygen) and some of the substances which are important in living organisms have still larger molecules; for instance, an insulin molecule¹ con-

¹ Insulin is produced in the healthy human body in a portion of the pancreas gland. If the gland does not produce enough of it the body cannot oxidize the sugar contained in the food; this condition is called diabetes. Giving the patient insulin obtained from animal glands restores his ability to utilize his food and removes the symptoms due to the presence of sugar in the blood.

tains several thousand atoms. On the other hand, the gas with which neon signs are filled consists of single neon atoms bouncing about in the glass tube; it is sometimes convenient to speak about neon molecules, each consisting of one atom only. Not all elements are like this. The oxygen in the air around us has molecules which consist of two oxygen atoms, and quite a number of gases are like that, for instance, hydrogen, nitrogen (the gas of which 80 per cent of the air consists, the other 20 per cent being mainly oxygen), chlorine and others.

You may ask what I mean by the statement that rock salt consists of sodium chloride molecules. We have seen

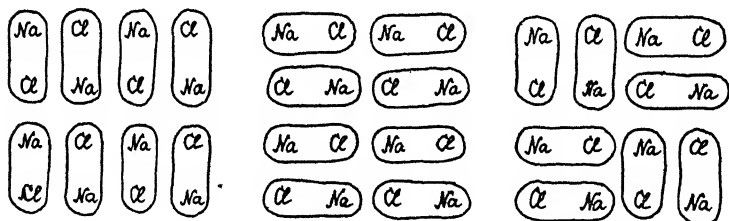


FIG. 11. The same arrangement of chlorine and sodium atoms (corresponding to their arrangement on the face of a rock-salt crystal—compare Fig. 2) is shown three times, illustrating different ways of “pairing off.” Na (for natrium) is the chemical symbol for sodium.

that the sodium and chlorine atoms in a salt crystal are arranged in a kind of regular network with each sodium atom surrounded by six chlorine atoms and each chlorine atom by six sodium atoms. Where are the molecules? One can of course always arrange the atoms into pairs. Figure 11 shows a small piece of a rock-salt crystal and indicates several of the ways in which the atoms can be “paired off.” The mere fact that there are several such ways indicates that the process is purely arbitrary, that, in bald fact, there are no molecules in a rock-salt crystal. Some people like to say

that the whole crystal forms one huge molecule, and I see no way of preventing them. However, there is one fact to encourage those who prefer to imagine the crystal as being built up of sodium chloride molecules. If you heat salt to a bright-red heat it melts and begins to evaporate. The vapor which it gives off is found to consist of molecules each of which is made up of one sodium and one chlorine atom.

Oddly enough, if you dissolve salt in water, something different happens. The sodium and chlorine atoms do not combine into molecules, like people getting up in order to dance, but stroll off singly. Furthermore, they are all electrically charged. If you dissolve sugar nothing of the kind happens; the solution contains complete sugar molecules, without any electric charges.

The way to find out about these things is to put two metal plates into the solution and connect them to a source of electric potential, for instance, to the two poles of a flashlight battery. If you do this with distilled water you will find that very little current goes through. Dissolving sugar in the water makes very little difference. But if you

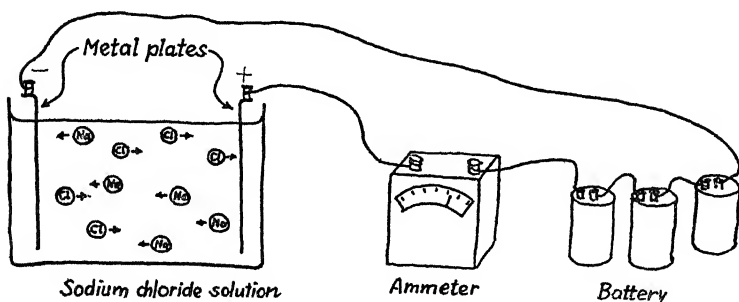


FIG. 12. Electrolysis. Current from a battery passes through an ammeter (to measure the current) and through an electrolyte, in this case a solution of sodium chloride (ordinary salt) in water. The chlorine ions travel to the positive plate (the anode), the sodium ions to the negative plate (the cathode).

dissolve some salt the current increases many times, and you will also observe that gas bubbles are formed on the metal plates. The water around the plate which is connected to the positive pole becomes greenish and smells of chlorine, and chemical analysis shows that the water around the negative plate contains excess sodium in the form of caustic soda. It is seen that the sodium and chlorine atoms in the solution are attracted to the two plates. Since the sodium atoms go to the negatively charged plate they must themselves carry a positive charge (as you know, opposite charges attract each other), and, similarly, we must assume that each chlorine atom carries a negative charge. Such charged atoms (or molecules) have a special name: they are called "ions." To summarize: kitchen salt, if dissolved in water, consists of positive sodium ions and negative chlorine ions.

How do the sodium and chlorine atoms suddenly acquire an electric charge on being dissolved? The answer is: they don't. They are already charged. When I said that a salt crystal is a regular network of sodium and chlorine atoms I was not quite precise; I ought to have said "ions" instead of "atoms." The reason you don't notice these electric charges is that there are just as many positive as negative ones, and that they are evenly distributed. Even if you squeeze a rock-salt crystal in a vise (of course not so hard that the crystal breaks) the positive and negative ions are displaced by the same amount, and their electric charge remains unnoticeable. With certain other crystals it is a different story; for instance, if you squeeze a quartz crystal, the positive silicon ions and the negative oxygen ions are displaced by different amounts and the crystal as a result becomes positive on one side and negative on the other. This phenomenon ("piezoelectricity") has found impor-

tant technical applications, for instance, in radio engineering, and some phonograph pickups use piezoelectric crystals. A rock-salt crystal is too symmetrically constructed to show piezoelectric behavior, but there are other ways (too complicated to be explained clearly in a short space) of showing that it is made of ions, too.

Let us return to our solutions. This phenomenon of "electrolysis," the separation of positive and negative ions by means of an electric current, has been of the greatest importance in the development of chemistry and physics, and also has important practical applications, of which electroplating is the best known. A metal part to be silver-plated is immersed in a solution of a suitable silver salt, and an electric current is passed between it and another metal plate. The silver ions travel toward the metal part and deposit themselves on it in a firm shiny layer.¹ The amount of silver deposited can be regulated by varying the strength of the current or the time interval during which the latter flows. Actually, the amount deposited during a given time is so accurately proportional to the current that a method for measuring electric currents has been based on this. The current is passed through a solution of silver nitrate for a certain time and the amount of silver deposited on a platinum foil is found by weighing the foil before and after the deposition. A current of one ampere will deposit 1.118 milligrams of silver per second. Of course, one normally measures currents simply with an ammeter, but ammeters have to be calibrated and this is a method of doing it.

The amount deposited per second by a current of one

¹ The reason we do not get a layer of sodium when we electrolyze a solution of sodium chloride is that sodium reacts with water, forming caustic soda, which dissolves in the water. Sodium can be deposited if one avoids the presence of water, for instance by electrolyzing molten sodium chloride.

ampere has been carefully measured not only for silver but for a great many other elements. In a number of cases it was found that the amount, while different in terms of weight, was the same if reckoned by the number of atoms. For instance, if sodium is deposited the amount is only .238 milligram per second, for one ampere. This amount is precisely as much less than the amount for silver (1.118 milligrams) as the atomic weight of sodium, 23, is smaller than the atomic weight of silver, which is 108. Hence a given current will deposit just as many sodium atoms as silver atoms in the same time. This must mean that a sodium ion carries the same amount of electric charge as a silver ion. An electric current is nothing but the passage of a certain amount of electric charge per time unit; if the same current causes the passage of the same number of ions, be they sodium or silver ions, then these two kinds of ions must carry the same charge.

I said before that in some cases the number of atoms transferred was the same as with silver; in other instances this is not so, which must mean that those ions carry a charge different from that of silver ions. That is true, but it turns out that in these cases the charge of the ion is just two, three, or four times greater than the charge of the silver ion. It would seem that the charge of the silver ion represents a kind of natural unit of electric charge, and it would be tempting to guess that not only ions but all electrically charged bodies always carry a whole multiple of this unit. Such a guess would be difficult to verify with moderately large bodies, for the smallest measurable charge on such a body would correspond to many thousands of those units; it would be impossible to measure it accurately enough to decide whether or not it is a whole multiple of the unit. But by using very small bodies, namely, tiny oil

drops visible only through a microscope, Millikan succeeded, in 1911, in measuring their charge accurately enough to show that they were indeed multiples of our unit. Would you like to know how this is done? Come along to the laboratory, and I will show you.

IX

THE OIL DROP EXPERIMENT

THIS METAL cylinder, about six inches across and six inches high, contains all the essential parts of the setup. The brass tube which sticks out to one side is the microscope; if you look through the eyepiece you will see the oil droplet. You see nothing but blackness? Then there probably is no oil drop. Let me put a new one in. There is a little atomizer on top, such as you find on perfume bottles, only here the bottle contains oil; if I give the rubber ball just one squeeze it will produce a fine spray of oil, and with luck one of the droplets will fall right through the little hole on top of the metal cylinder. Just let me adjust the field. Right, now you can look yourself. You will see the oil droplet as a tiny point of light, like a star.

The reason it floats quietly in mid-air instead of falling is that it is electrically charged, and that there are two electrically charged plates inside the metal cylinder. Let me explain this with the help of a diagram (Fig. 13) which shows what is inside the metal cylinder. The main parts are two metal plates, both horizontal, held by insulating supports. Each plate is connected to one of two insulated terminals, and from there wires lead to an adjustable voltage supply (essentially a battery and a resistor with a gliding contact, like the volume control in your radio). Right now we have a negatively charged droplet in our apparatus; I had to make the top plate positive and the bottom plate

negative in order to prevent the droplet from falling. It is really a little like electrolysis; there an electric field was provided to set the particles (the ions) moving; here the particle would move on account of its weight, but we pro-

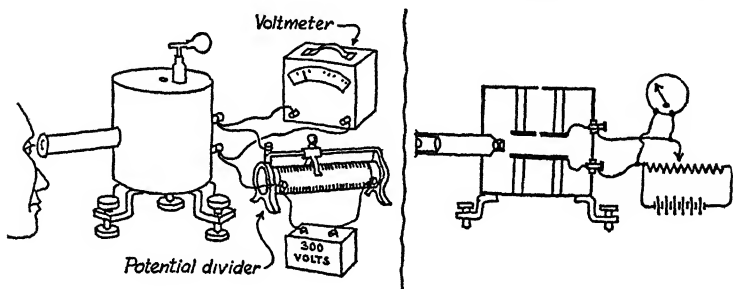


FIG. 13. Millikan's oil drop experiment. The oil drop is kept floating by an electric field between the two horizontal plates which are supported by insulating posts from above and below (see right-hand drawing). A microscope serves to watch the oil drop. The electric potential difference between the plates is adjusted by means of the potential divider, and measured by means of the voltmeter.

vide an electric field to prevent this. If you watch the particle you will see that it drops if I switch the electric field off for a moment. What do you say, it went up? Why, of course, the microscope gives an inverted image, so that everything looks upside down. So you see, the droplet really did drop when I switched the field off.

Of course the droplet will fall slowly even if I merely weaken the electric field a little; if I make the electric field too strong its pull becomes greater than the weight of the droplet, which will then move up. By watching the droplet through the microscope and adjusting the field carefully one can get it so that the droplet remains perfectly motionless for a long time and then we know that the upward pull of the electric field is exactly equal to the downward pull of the particle's weight.

But how can we find the weight of the oil drop? It is many, many times too light to be weighed even on the most sensitive balance. Yet there is a very simple trick by which the weight of the oil droplet can be found right on the spot. This trick consists in measuring the speed with which the particle drops when the electric field is switched off. You may have noticed that there are two fine horizontal lines in your field of view, looking like fine cracks in a door with a lighted room behind. By increasing the field for a short time we first lift the droplet high enough so that its image appears below the lower one of those two lines (remember, everything looks upside down!), and then we switch the field off entirely and measure, with the help of a stop watch, the time it takes the particle to traverse the distance between the two lines. These lines are really illuminated scratches on a glass plate inside the eyepiece, and by taking the microscope out and looking through it at a finely divided scale¹ one can find how far two points have to be apart for their images to fall on the two lines in the eyepiece.

The reason the droplet falls so slowly (only a fraction of a millimeter per second) is the air resistance. In ordinary life this is not very important, although you feel it when you go fast in an open car. Smaller bodies feel it much more strongly. If you drop a pingpong ball from the top of a skyscraper it will be seen floating down at a constant speed of a few yards per second (except for the first second or so which it needs to acquire this speed). A solid wooden ball of the same size will acquire a greater speed; obviously

¹ Some optical firms make scales with a hundred lines to a millimeter, drawn on glass with a machine similar to the one used for making diffraction gratings, described on page 42.

the speed depends not only on the size of the ball but also on its density. Now we know the density of our droplet, for we can measure the density of the oil of which it consists; the way the velocity of fall depends on the size can be found by experiments. Hence, from the speed with which our droplet falls when the field is switched off, we can determine its size and from this its weight (since we know the density).

Once we know the weight of the droplet it is a very simple matter to calculate its charge from the voltage we have to apply to the two horizontal plates to keep it suspended. I shall tell in the next chapter how this calculation is done and also how various electrical units have been chosen to make such calculations easy. Here I shall merely report the result: the charge of the droplet is found to be always a whole multiple of a certain unit charge, and the size of this unit charge is such that 6.25×10^{18} of them have to flow through a wire each second to make up a current of one ampere.

Do you notice that this figure can again be used to determine the weight of a hydrogen atom? We know that one ampere can deposit 1.118 milligram of silver per second, or 1.118×10^{-3} gram. If we divide this amount by 6.25×10^{18} , the number of charge units carried each second by a current of one ampere, we get the weight of a single atom of silver (provided that the silver ions carry the same charge unit which resulted from our oil drop experiment). The result is 1.79×10^{-22} gram. The atomic weight of silver being 108, we have to divide the weight of one silver atom by 108 in order to get the weight of one atom of hydrogen. If we do this we get 1.66×10^{-24} gram.

This result is again very nearly the same as that found

before, although the method is an entirely different one. Checks like this give the physicist the feeling that what he does makes sense, that it hangs together.

You may ask why an apparatus for doing the oil drop experiment is found in this laboratory, if the experiment was already made by Millikan in 1911. The reason is that students usually repeat it in the course of their training. It is much more instructive to do such an experiment oneself than to read about it in a book or hear of it in a lecture. By doing a number of selected experiments a student gets personally acquainted with a variety of techniques; some of them he may be able to use when he starts out on research of his own; the knowledge of others may stimulate him to invent new techniques of his own for solving new problems.

Till now I have spoken about atoms as if they were truly indivisible, just as the old Greeks (in particular Democritus) conceived them to be. For the purposes of chemistry this concept is indeed sufficient, provided one assumes that the atoms are endowed with special "affinities" whereby they like to attach themselves to other atoms, forming molecules. These affinities are very specific. Chlorine has a strong affinity to sodium, a measure of which is the considerable heat developed when sodium metal ignites upon contact with chlorine gas and forms sodium chloride. Yet it has very little affinity to oxygen, which in turn has strong affinity to sodium. If sodium and oxygen combine, one atom of oxygen combines with two atoms of sodium; on the other hand, zinc oxide contains one atom of zinc for each atom of oxygen, and in aluminum oxide there are three atoms of oxygen for every two of aluminum. Nor is the ratio always constant for the same two elements; for instance, one atom of oxygen can combine with one atom

of copper, forming a black compound, or with two, and a red compound results. The chemists take account of this fact by saying that the same element may have different "valencies"; they have also discovered numerous rules limiting the variability of valency. However, the nature of the forces which bind the atoms together in a molecule was for a long time not understood; they were called chemical forces and were thought to be different from all other forces known.

The discovery that atoms can carry certain electric charges suggests at once that the chemical forces may in reality be electrical forces. For instance, if a sodium chloride atom consists of a positively charged sodium ion and a negatively charged chlorine ion, the mutual attraction between the two opposite charges would explain the molecule holding together. It would also explain why one sodium ion binds just one chlorine ion; for if we were to add another one the resulting molecule would no longer be electrically neutral, and the smallest grain of a compound made of such electrically charged molecules would have so terrific an electric charge that it would explode due to the mutual repulsion of its molecules. Hence molecules must normally be neutral, although a molecule may occasionally carry an electric charge, as did the oil droplet; it is then called a molecular ion. However, I have stated before that certain elements form ions with more than one charge unit. For instance, in solutions of zinc chloride, the zinc ion carries two positive charges; one might therefore expect that it can bind two chlorine ions to form zinc chloride, and that is indeed the case. Likewise, aluminum forms ions with three positive charge units, while oxygen likes to form ions with two negative charges; hence two aluminum ions and three oxygen ions have to come together to form a neutral

molecule, and that is just the long familiar composition of aluminum oxide.

This simple explanation sounds very attractive, but we get into trouble when we wish to explain that chlorine gas is composed of molecules each of which consists of two chlorine atoms. For we must assume either that both are neutral atoms, in which case there is no electric force to hold them together, or that one is a positive, the other a negative ion. That, however, would make the molecule unsymmetrical and that is in contradiction with other evidence. What then holds the two chlorine atoms together? Another obvious question is: Why does sodium form ions with one positive charge, zinc ions with two positive charges, chlorine ions with one negative charge, and so on? I shall try to indicate later how, with the help of quantum theory, atomic physicists have been able to give answers to questions of this kind, but we have to take a few intermediate steps before I can do that. Right here I should like to say that the idea of the electrical character of chemical forces has come through with flying colors. In the next chapter I shall therefore speak in some detail about the properties of electricity, and of the system which the physicists have developed to measure quantities of all kinds, including electrical and magnetic ones.

X

ABOUT WEIGHTS AND MEASURES

YOU MAY have wondered why I insisted on using centimeters and grams instead of the more familiar inches and pounds. I did this to acquaint you with the system of measurements used by the atomic physicists, called the C.G.S. system or the absolute system.

Strictly speaking there are no absolute measurements. Any measurement is relative in the sense that it establishes a relation between the quantity to be measured and some standard quantity of the same kind. If you measure the length of a piece of rope you establish how many times longer it is than your yardstick. If you weigh a sack of coal you find how many times heavier it is than a pound weight. If you measure an electric voltage you find how many times larger it is than the voltage of a certain standard source of voltage; to determine the brightness of a lamp bulb you compare it (directly or indirectly) with a standard oil lamp. There are many different kinds of physical quantities and each requires the setting up of an appropriate standard before we can even start to measure it.

In the old times these standards were set up in a more or less haphazard manner. Familiar objects of more or less constant properties were selected, as you can see from the still-used units of "foot" and "grain." While the length of a house was measured in feet, the distance from one town to another was measured in miles (a mile was originally

equal to a thousand double steps of an average Roman foot soldier). A foot is many times less than a mile and at first nobody worried about the ratio between the two. Since human feet are usually horizontal, a different unit, the fathom, was used for measuring depth. Various units arose the world over or originated within various professions; they often continued side by side, like the troy, avoirdupois and apothecary systems of weight in England.

But around 1800 a new system of measuring physical quantities emerged, originating in France, the country of logical thought. The idea was, first of all, to use only one standard for each kind of quantity. Instead of measuring lengths in feet, fathoms and miles, they were all to be measured in meters. The meter was defined as one ten-millionth of the distance between the pole and the equator of our earth. Subsidiary units, such as decimeter, centimeter, millimeter, and decameter, hectometer, kilometer, could be formed by successively dividing or multiplying by 10; none of this business of twelve inches to the foot, or sixteen ounces to the pound.

In the course of time the centimeter (one-hundredth of a meter) became the pet unit of the physicists, and eventually adopted as the fundamental unit of length, in preference to the meter. It may sound unfamiliar if you are told that the distance from Pittsburgh to Palm Beach is 1.53×10^8 centimeters, rather than 950 miles; but in physics, where the diameter of an atom and the distance to the moon may appear in the same calculation, it simplifies matters to stick to one unit.¹

The other important idea in the new system was to

¹ On the other hand, the mental alacrity and unceasing vigilance required for the successful handling of inches, ounces, acres, feet, fathoms, pounds and stones have undoubtedly some connection with the successful handling of world political problems by the English-speaking races.

have only a small number of independent units. There are only three in all. The first, the centimeter, we have mentioned. The next is the unit of mass, called gram, which is defined as the mass of one centimeter cube of water at the temperature at which water is densest (4° centigrade, or about 39° Fahrenheit). Here again, subsidiary units were to be formed by multiplying or dividing by ten, but of these only the kilogram (thousand grams, or about 2.2 pounds) and the milligram have come into common use.¹

The third unit required is the unit of time, one second. This unit really goes back over three thousand years, to the old Babylonians, the fathers of astronomy. They divided the day into twenty-four hours, the hour into sixty minutes and the minute into sixty seconds, and all astronomy to this day descends directly from their accurate and reliable observations. Since the measurement of time was thus in a very satisfactory state the French reformers had no reason to introduce a new time unit, nor did they interfere with the use of the other units, minute, hour, day, etc. So the second is still what it has been for a very long time, namely $1/86,400$ ($86,400 = 24 \times 60 \times 60$) of a day or, to be precise, of one average solar day.²

These three units form the basis of the C.G.S. system (for centimeter-gram-second), also called (somewhat arrogantly) the absolute system. All physical measurements can be based on these three units. Speeds are measured in centimeters per second or, briefly, cm/sec. My car makes about 3×10^3 cm/sec (but I don't like to go that fast); sound travels at 3.3×10^4 cm/sec, light at 3×10^{10} cm/sec. The

¹ However, Austrian housewives buy their groceries by the "Deka," brief for decagram, which is ten grams (about one-third of an ounce).

² Mainly because of the elliptic path of the earth, the length of the solar day, measured from noon to noon, varies by about one minute. Noon is defined as the instant when the sun crosses the meridian.

unit of force is called one dyne; it is defined so that if it acts on a body of one gram weight which is free to move, then the speed of this body increases each second by one unit of speed, that is, by 1 cm/sec. If the motion of a falling body is studied (as by Galileo) we find that its speed grows every second by an amount of 981 cm/sec, hence the force of gravity which makes it fall amounts to 981 dynes for every gram of it. Therefore, if a one gram weight is on a table it exerts a force of 981 dynes upon it.

If you move a body against an opposing force, you do work, and the unit of work—called one erg—is defined as the amount of work you do if you move a body by one centimeter, against an opposing force of one dyne. Going upstairs to the second floor you move your body up by about ten feet, or 300 cm, against an opposing force of 981 times the weight of your body in grams. If you weigh 140 pounds, which is 6.4×10^4 grams, the work you do in going upstairs is $300 \times 981 \times 6.4 \times 10^4$ ergs = about 2×10^{10} ergs.¹ You see that the erg is a very small unit for ordinary human needs (and so is the dyne), but that does not worry the physicist.

One of the oldest dreams of human beings, and one which stimulated the development of physics as much as the desire to make gold stimulated chemistry, is that about a machine which would increase one's capacity for doing work, or which would even produce work out of nothing. A lever may enable a man to lift a load ten times heavier than what he could lift with his bare hands. Yet, while the force which opposes him has been reduced by a factor ten, he has to move his end of the lever through a distance

¹ If you walk on a level road there is no force to oppose you, except air resistance, which is very small at walking speed. All the same, you do work against the frictional forces inside your own body, and that is why you get tired.

ten times greater than the height by which the load is to be lifted; therefore he does just as much work as if he did not use a lever. It took a long time before people acknowledged that work cannot be created out of nothing, and their numerous attempts at doing just this resulted in the emergence of one of the most fundamental principles of science, the *principle of the conservation of energy*.

Energy may be called stored work, or the capacity for doing work. If I wind my grandfather clock I do work in lifting the weight; this work is stored in the weight as "potential energy" and gradually used up during the week, as the weight sinks down, to keep the clock going. The work I do in winding my watch is stored as "elastic energy" within the main spring. If I throw a stone up into the air I give it energy of motion, or "kinetic energy"; as the stone rises its speed and hence its kinetic energy diminishes, but its potential energy increases, just like that of the weight in my grandfather clock when I wind it. After the stone has passed its highest point its kinetic energy increases again, while its potential energy decreases. When the stone hits the ground its kinetic energy suddenly disappears; but the stone and the ground get slightly heated by the impact, and the heat generated contains just as much energy as the kinetic energy which disappeared. When a steam engine pulls a train out of the station with gradually increasing speed the opposite process takes place, the conversion of heat energy into kinetic energy. All these things are illustrations of the principle of the conservation of energy (often briefly called *the energy principle*) which says that energy is never created and never disappears, but merely changes form. Since energy is stored work, it can be measured in the same units as work, that is, in ergs, although sometimes other units are more convenient.

All this seems to have nothing to do with atoms; but atomic physics is a part of general physics, which rests to a large extent on the concepts of force and energy as just explained, and in which accurate calculations are greatly facilitated by the use of a consistent way of measuring, such as the C.G.S. system. In particular, we have seen that electric forces play a great part in holding atoms together, and the fact that electrically charged bodies always carry a whole multiple of a certain fundamental charge is obviously an important clue to the ultimate structure of matter. So I shall have to talk a great deal about electrical phenomena in what is coming, and if I want to make things clear I must make use of some of the concepts which physicists have created for the purpose of understanding electricity.

You know that a piece of glass rubbed with silk becomes electrically charged; it attracts the silk, and repels another piece of glass which has been similarly rubbed. Two pieces of silk repel each other if both have just been used to rub glass. From this and similar experiments we conclude that bodies can carry two kinds of electric charges, which are called positive and negative. Two bodies which carry charges of the same kind repel each other; if they have charges of different kind they attract each other. If two equal charges of different kind are brought together they neutralize each other, that is, they both disappear and the body becomes non-electric. This naturally leads to the idea that all bodies contain both positive and negative electricity, but normally in equal amounts so that neither of them is noticeable. This idea is supported by the fact that when you rub glass with silk both become electrically charged, the glass positive and the silk negative. This could be explained by saying that some of the positive electricity always contained in the silk had been transferred to the glass,

in the process of rubbing, or by saying that some of the negative electricity of the glass had been rubbed off by the silk. It is probable that the second answer is the right one; but it is a fact—and there is an element of irony in it—that while our knowledge and command of electricity have expanded in the most brilliant fashion, the very phenomenon through which electricity was discovered is still not well understood. We still cannot give a proper explanation why, if glass and silk are rubbed together, the glass should become positive and the silk negative, and not the other way round.

Let us now define some electrical units in accordance with the principles of the C.G.S. system. The unit electric charge is defined as that which, if—no, let me start again. Two small bodies, each carrying one unit charge, placed one centimeter apart, exert a force of one dyne on one another. In Chapter IV I stated that it is convenient to say that in the neighborhood of an electrically charged body there exists an electric field, the intensity of which decreases as we move away from the body. We can at once define a unit of electric field intensity, namely, the electric field in which a unit electric charge (which we have just defined) is pulled along with a force of one dyne.¹ If I get hold of the body and move it against the pull of the electric field I am doing work, and the work is stored as potential energy of the charged body, just as the work done in winding the grandfather clock is stored as potential energy of the clock weight. This leads to the very important concept of the “electric potential.” If I can move a charge from one point A to another point B, or from B to A, both without doing any work, I say that the two points have the same

¹ From our definition of the electric charge unit it follows that the field one centimeter away from a unit charge is just the unit field.

electric potential; if I have to do work in order to move the charge from *A* to *B* then *B* has a higher potential than *A*, and I measure the potential difference by the amount of work in ergs which I have to do to move a positive unit charge from *A* to *B*. This last stipulation is important because a negative charge is pulled with the same force, but in the direction opposite that of an equally strong positive charge; hence what would appear as the higher potential to a positive charge would seem a lower potential to a negative charge, and we must therefore stipulate the kind of charge to be used for measuring potentials in order to get consistent results.

The electric potential may be better visualized if I point out that it plays the same role in electricity that the level does in ordinary life. If two points *A* and *B* are on the same level, then I can convey a weight from *A* to *B* without doing work, for instance, by rolling it on a horizontal track, or by swinging it across with a rope.¹ If the point *B* is at a higher level than *A*, one has to do work in order to lift the weight from *A* to *B*.

Water in an open vessel has a horizontal surface, that is, all points on its surface are at the same level. If two vessels are connected by a pipe, the water will flow from the higher level to the lower until the two levels have become equal. If one installs a pump we can pump water continuously back into the higher basin, and in this case the flow through our pipe will go on indefinitely, as long as the pump is kept running. If a stronger pump is installed the water in the upper basin will rise to a higher level,

¹ In reality there is always some friction, and one has to do some work to overcome it. However, friction can be reduced almost indefinitely by the use of ball bearings, etc. (The manufacture of these contrivances is not "work" as the physicist means it.)

its pressure will be higher, and a stronger current of water will run through our pipe.

All these things have counterparts in the field of electricity. The counterpart to an open vessel is an "electric conductor," such as a piece of metal, in which electric charges can move about freely. If an electric charge is placed on a conductor it will immediately distribute itself in such a fashion that the electric potential is the same everywhere on it. If two conductors at different potentials are connected by a wire, charges will flow from the higher to the lower potential. This electric current will diminish and eventually cease (usually within a small fraction of a second) when the potential in the two conductors has become equalized. If, however, a "pump" for electricity is installed, such as an electric battery or one of those electric generators to be found in power stations, then the potential difference can be kept up by pumping charges continuously back from the lower to the higher potential; the current will keep flowing as long as the generator is running.

An electric current is therefore nothing but streaming electric charges, just as a current of water is streaming water. However, there are two kinds of electric charges, and a current flowing from A to B may be a stream of positive charges moving from A to B or a stream of negative charges moving from B to A. Which is it in reality?

If the current flows through a solution of sodium chloride the answer is: both. We know that positive sodium ions are moving one way and negative chlorine ions the other way; each makes up one-half of the total current which flows through the solution. But what about the copper wires which lead the current into the solution and out again? However long you continue your experiment, no chlorine or sodium is found in the copper wires, so the current

cannot be carried by sodium or chlorine ions. Perhaps it is carried by copper ions? But you can make a chain of different metal wires, say copper, gold, silver, iron, nickel and any others, and pass a current through the chain for as long as you please; each link in the chain will still consist of the same metal as in the beginning, without any contamination by the metal of the neighboring links. Therefore, the current in metals must be carried by something which is a common constituent of all metals and thus can pass from one metal to the other without affecting their chemical nature. This something was not given a name until ways had been discovered of liberating it from its metal prison; it was then found that it consists of small particles all alike, called electrons. In the next chapter I shall tell you more about them.

After all this fine talk about absolute measurements I have to confess that the electrical units which we, along with engineers and others use in the lab, are not the absolute units. But at least they are connected with the absolute units through some very simple numerical factors. Potential differences are measured in units called one volt (after Alessandro Volta, the father of electrical batteries), and one volt is one three-hundredth of an absolute unit of potential; or one absolute unit of potential is 300 volts, if you like it better that way. Instead of the term "potential difference" (or simply "potential" where the meaning is clear) I shall often use the more common word "voltage," which expresses the fact that this quantity is measured in volts. Electric currents are measured in units called one ampere (after A. M. Ampère, who made fundamental contributions to our knowledge of electric currents), and one ampere is 3×10^9 (three billion) absolute current units, or in other words, a current where 3×10^9 absolute charge units pass

through the wire every second. There are many other units with which I won't bother you since my main purpose is to explain the methods by which atoms are explored, and for this those other units are not needed.

Although we use the "practical units" volt and ampere in our experiments we often convert them into absolute units when we do calculations. For instance, the fact that 6.25×10^{18} electrons per second represent a current of one ampere means that this number divided by 3×10^9 , or 2.08×10^9 electrons make up one absolute charge unit. Therefore one electron carries 4.80×10^{-10} absolute charge units (1 divided by 2.08×10^9).

XI

THE LIBERATION OF THE ELECTRON

THOMAS A. EDISON discovered that electrons can be made to "evaporate" from metals simply by the use of heat. He made a lamp bulb which contained a metal plate in addition to a filament. As long as the filament was cold no current would pass between the filament and the metal plate, even if a fairly high electric potential was applied between the two. However, when the filament was heated a current started to flow, provided the plate was positive with respect to the filament; if it was negative the heating

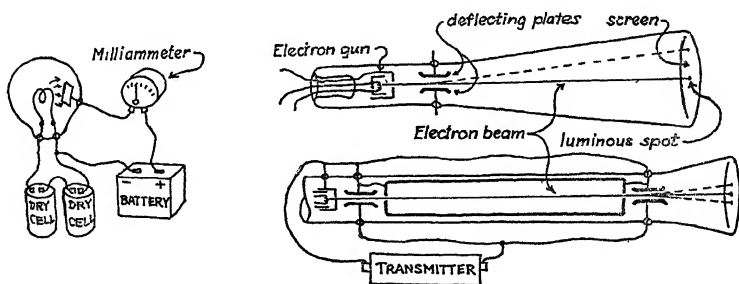


FIG. 14 The Edison effect A white-hot metal filament (two dry cells are used to heat the filament) in an evacuated bulb emits electrons which can be collected by a metal plate in the same bulb. The milliammeter is used to measure the current which these electrons carry. To the right: Two electron beam tubes; the top one to demonstrate the deflection of an electron beam in the electric field between the two deflecting plates, the bottom one to measure the speed of electrons (see text)

of the filament did not produce a current. This shows that negative charges are liberated by the hot filament. These charges can be persuaded to come to the plate by making the latter positive but they will not cross the vacuum against the repellent force of a negatively charged plate.

This simple observation was the starting-point of that huge scientific and engineering development which is now covered by the name of "Electronics." X-ray tubes, radio tubes, television tubes and fluorescent lamps (not to mention many others) are all descendants of Edison's little lamp bulb with the metal plate. The way in which the electron, discovered only half a century ago, has come to be one of the most versatile and powerful servants of mankind makes a fascinating story, and Edison's little lamp may be said to compare favorably with Aladdin's lamp of ancient fame. However, this story has been told by others (for instance, by Harrison in his "Atoms in Action") and I shall here confine myself to the purely scientific implications, which are no less fundamental.

A television tube is perhaps the best instrument through which to familiarize oneself with the properties of free electrons. At the narrow end is a so-called electron gun; this contains a heated "cathode" usually covered with some special oxide to facilitate the evaporation of the electrons, and some electrically charged metal shields which draw the electrons all to one side so that they emerge from the gun in a narrow beam, like the stream of bullets emerging from the muzzle of a machine gun. If the metal parts outside the gun are all at the same potential the electrons will move through the tube in a straight line until they hit the screen at the end of the tube. The screen is covered with some material which gives off light when hit by electrons and the spot where the electron beam hits the screen thus

becomes visible as a brilliant spot of light.¹ The tube I have drawn (top right half of Fig. 14) also contains two metal plates which are placed so that the beam has to pass between them (not all television tubes contain these plates). If one of these plates is made positive with respect to the other, then the electrons during their passage are attracted toward the positive plate and the whole beam gets deflected; the luminous spot on the screen shifts. If one changes the potential difference between the plates suddenly, the spot appears to jump instantly without any visible delay. Actually, there must be a delay since the electrons must take some time to travel the distance from the deflecting plates to the screen, and the fact that no delay is noticeable merely indicates that they travel very fast. Actually, there is a delay of about 10^{-8} second, that is, one hundred-millionth of a second.

A hundred-millionth of a second is a very short time interval, but modern high-frequency technique is used to such short times. The current in the transmitting aerial of a radio station operating on fifty megacycles changes direction a hundred million times a second, so the time between two changes is just the time we are looking for. If we have a small fifty-megacycle transmitter it is an easy matter to measure the speed of our electrons.

For this we have to build a new tube which contains two pairs of deflecting plates, separated by a metal tube about a foot long (see Fig. 14). The deflecting plates are connected to the transmitter as shown. As long as the transmitter is not operating the electrons run straight through the whole tube and hit the middle of the screen. But if

¹ The material used on the screen is similar to that on a luminous watch dial, only, of course, it contains no radioactive material. The amount of light produced by a single electron is too weak to be visible.

the transmitter is switched on the electrons have a hard time. The potential difference between the first two deflecting plates keeps oscillating between a large positive value and an equally large negative value, and only those electrons which slip through at the very instant the potential difference is zero can even reach the second pair of deflecting plates; all the others get deflected from their straight path and miss the hole at the end of the metal tube.

Now let us consider those electrons which passed through the deflecting plates at just the right time. As soon as they have entered the metal tube the electric field between the deflecting plates rises again but our little troop of electrons is safe, protected by the metal tube, until they enter the second pair of deflecting plates. What happens there depends on how much time they have spent in the tube, and, therefore, on their speed. If they have spent just one hundred-millionth of a second, then the field between the deflecting plates will have just dropped to zero again and they will slip through without deflection. If their speed is different they don't arrive in time and get deflected, some one way, some the other way, depending on whether they have passed the first deflecting plates as the potential was changing from positive to negative or from negative to positive. The luminous spot will then be split into two spots.

The speed of the electrons depends on the voltage with which they have been accelerated, just as the speed of a falling stone depends on the height from which it has been dropped. By adjusting the accelerating voltage, that is, the potential difference between the electron-emitting cathode and the metal tube in which the speed of the electrons is measured, we can make the two light spots on the screen merge into one, and then we know that the electrons travel at such a speed that they spend exactly 10^{-8} sec in the metal

tube.¹ If our tube is just 30 cm long this means that their velocity is $30 \cdot 10^8$ or $3 \cdot 10^9$ cm/sec, only ten times less than the velocity of light. The actual experiment shows that in order to get electrons of this velocity we must accelerate them with a potential of about 2560 volts.

Now this is not just a fact to be written down and locked into a drawer against the day we may want to have electrons with a speed of exactly $3 \cdot 10^9$ cm/sec. On the contrary. From this fact we can immediately calculate the mass of a single electron. The calculation is as follows: Each electron is accelerated by a potential difference of 2560 volts, or in absolute units, 2560 divided by 300, or 8.53 absolute potential units. The charge of the electron is 4.80×10^{-10} absolute charge units. If we were to push an electron up against a potential difference of 8.53 absolute units, we would do work to the amount of $8.53 \times 4.80 \times 10^{-10}$, or 4.10×10^{-9} erg; if the electron is allowed to drop through this potential difference it acquires 4.10×10^{-9} erg in kinetic energy. Now there is a very simple relation between the speed and mass of a moving body and its kinetic energy. If we use absolute units throughout we get the kinetic energy of a body simply by multiplying half its mass by the square of its velocity. In our case we know the kinetic energy and the velocity of the electron but not its mass. If we divide the kinetic energy by the square of the velocity we get half the mass. Let us do this. The square of 3×10^9 is 9×10^{18} ; if we divide 4.10×10^{-9} by 9×10^{18} , we get

¹ You may ask, how do we know that they do not spend exactly $2 \cdot 10^{-8}$ sec or $3 \cdot 10^{-8}$ sec? In this case they would also get through without deflection. However, such a misinterpretation would quickly show up as soon as one started to vary the accelerating voltage over an appreciable range. In particular, by raising the speed by a factor not greater than 2, we would again find an adjustment where the two spots merge into one, whereas, if our interpretation is correct, this is not possible.

4.55×10^{-28} gram for half the weight of an electron. Hence an electron weighs 9.1×10^{-28} gram.

If we compare this figure with the weight of a hydrogen atom, 1.67×10^{-24} gram, we see that the electron is about 1830 times lighter. It is thus by far the lightest particle that we have come across, and no lighter particles are indeed known to physicists.

Now I should like to describe another method for measuring the mass of the electron. This method was historically the first to be used; it is technically simpler, but more complicated to explain. The reason I want to discuss it is that its importance goes far beyond its original purpose, as you shall see very soon.

This method depends on the effect of a magnetic field on moving electric charges. You can observe this effect in a crude way by bringing a magnet near to the screen of a television set; the image will be distorted and shifted in the neighborhood of the magnet, indicating that the electrons are being deflected where they pass close to the magnet. The phenomenon can be observed much more clearly with a tube in which the electron beam itself is visible and not merely the spot where it strikes the wall. I remember once visiting a German industrial research laboratory (in the days before Hitler). Entering one room, the scientist who showed me around said, "Dr. Brüche is on holiday, but perhaps I can make his setup work for you." There was a huge glass bulb on the table, perhaps two feet in diameter, like an enormous soap bubble. My guide fumbled among some switches and suddenly, as if by magic, a luminous blue beam appeared inside the bulb, sprouting from the little electron gun at the bottom like an ethereal blade of grass. There were some small magnets on the table and if I moved one of them the electron beam swayed like a grass in the

wind. As long as the magnet was kept quiet the beam would be quiet too, but it followed instantly any movement of the magnet. If the magnet was brought close to the bulb the electron beam would coil itself up into amazing shapes only to uncoil itself like a steel wire released, as soon as the magnet was removed. I could have played with it for hours. Incidentally, this apparatus was there for the sole purpose of impressing and entertaining visitors; it was not used for research.

The curious thing is that a magnet neither attracts nor repels the electrons; it waves them to one side like a traffic cop. If you hold one pole of the magnet against the wall of the bulb, the beam is deflected neither toward the magnet nor away from it, but sideways, to the right or the left, depending on which pole of the magnet you are holding against the bulb. You probably know that an electric current can deflect a magnetic needle; I have already mentioned the fact in Chapter IV. It is obvious then that a magnet must also exert a force on an electric current, and it was the French physicist Ampère who discovered this effect and its laws. The deflection of the electron beam is really the same thing: the electron beam consists of electrons all moving in the same direction, and therefore represents an electric current; the magnetic field exerts a force on this current and the electrons, not being confined to a wire, give way and are deflected.

In order to study the deflection properly it is best to make use of a homogeneous magnetic field, that is, one which has the same strength and the same direction everywhere, within a limited space of course. One can produce such a field by using a horseshoe magnet with pole pieces which are flat and parallel to each other, like the one shown in Fig. 15. Place an evacuated container between the pole

pieces and, with the usual electron gun, produce an electron beam which, if there was no magnetic field, would run in a straight line parallel to the pole pieces. The magnetic field will bend this beam into a line of constant curvature, that is, a circle, and if there is no obstacle the electrons will indeed describe a complete circle, eventually hitting

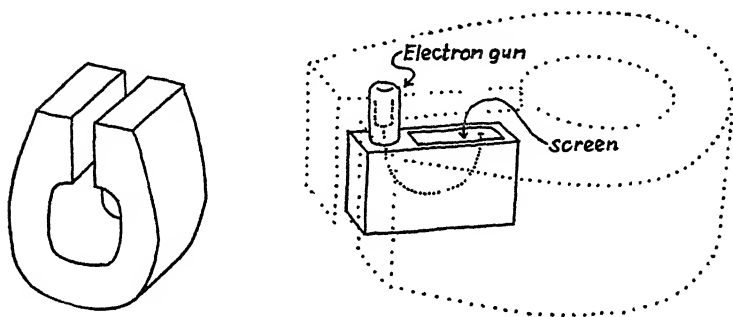


FIG. 15. A homogeneous magnetic field (that is, one of uniform direction and intensity) exists between the opposing parallel pole faces of a specially shaped horseshoe magnet (to the left). If an evacuated container, supplied with an electron gun and a luminous screen, is placed in such a field, the electrons are found to follow a circular path.

the back of the electron gun. We can stop the electrons after a semicircle by inserting a screen so that they produce a luminous spot where they strike; the distance between the spot and the electron gun tells us the diameter of the circle which the electrons would have described if we hadn't stopped them after a semicircle.

How strongly the magnetic field will deflect the electrons and hence how big a circle they will describe depends on the strength of the magnetic field and the speed of the electrons. I shall not bother you with the details of these calculations, although they are fairly simple. It will be

plausible to you that from the diameter of the circle which electrons of a given kinetic energy describe in a given magnetic field, one can again calculate their velocity and from this, as we have seen before, their mass. If our electron gun, in addition to ordinary electrons, should suddenly start to produce a new brand of electrons, four times heavier than ordinary ones, one can calculate that they would run in a circle twice as big, and hence a new spot would appear on our screen at twice the distance from the electron gun as the ordinary spot. Actually, only one spot is ever found and that one is quite sharp; this shows with considerable accuracy that all electrons are of the same weight.

You may ask, why does the electron beam trace its path through the vacuum as a luminous streak? Do the electrons by themselves emit light? No, they don't. The truth is, the bulb which I described to you was not completely evacuated. If we were to attach it to a powerful vacuum pump in order to remove the residual gas, the glow of the electron beam would get weaker and weaker and with the best vacuum that we can produce the beam would be invisible. The bulb was deliberately not too well evacuated so that one should be able to see the electron beam.

The light is not emitted by the electrons themselves but by those gas molecules which happen to get hit by one of the electrons. The process may be likened to the emission of sound from a wineglass tapped with a spoon; one may imagine the atom set vibrating by the impact of the electron and vibrating for a short time, sending out electromagnetic waves until the vibrations have died down. This analogy can be pursued at some length. A tapped wineglass emits a musical note, that is, sound of a definite frequency. The yellow light emitted from a sodium lamp is due to single sodium atoms which are struck by electrons made to pass

through the tube. If we analyze the light by means of a diffraction grating (see Chapter IV), we find that the light is all practically of one frequency, so the analogy with a wineglass is quite close. In a neon tube, you remember, the light emitted is a mixture of lights of several different wave lengths which show up as several red and yellow lines if we analyze the light. Atoms with such a "line spectrum" might be likened not so much to a wineglass as to a church bell, the peculiarly rich and vibrant tone of which is the result of a mixture of a number of different musical notes.

We can carry the analogy a step further. If a wineglass is struck too hard it breaks. Similarly, an atom can break if struck by an electron at sufficiently high speed. What happens then is that an electron gets knocked off the atom, which is thereby turned into a positive ion. By varying the voltage on an electron gun one can find out what kinetic energy an electron must have in order to be able to damage an atom in this fashion or, as one usually puts it, to ionize an atom.¹ One finds in this way that electrons must be accelerated by potentials of the order of 10 to 20 volts, depending on the kind of atom we want to ionize. It is easy to work out the kinetic energy of such an electron in absolute units (ergs) but it is often more convenient simply to use the voltage through which an electron has been accelerated as a measure of its kinetic energy. In this way we can say that it takes an energy of 10 to 20 electron-volts to ionize an atom. A sodium atom is particularly easy to ionize since it needs only about 6.5 electron-volts; on the other hand, it takes about 25 volts to ionize a helium atom. The low "ionization energy" of the sodium atom is obvi-

¹ This is not what is called "atom splitting." An ionized atom is only temporarily damaged; usually it very soon catches an electron from somewhere and is then its old self again.

ously connected with the readiness of sodium to form positive ions which we noticed on page 70.

A wineglass will ring however softly we tap it, although the sound will be very weak if we tap it very gently. Hence we might expect that atoms will emit light however slow the electrons are with which we hit them. But here our analogy breaks down completely. The fact is, if we want to produce light by electron impact on a given kind of atom, our electrons must have a definite minimum speed. For instance, if we want to get sodium atoms to emit their characteristic yellow light we have to hit them with electrons of at least 2.1 electron-volts; at 2.0 electron-volts no trace of light is produced. This is no matter of a gradual decrease of light output with decreasing electron energy; there is a sharp limit below which there is "nothing doing."

Now if you have read this book with almost superhuman attention you may remember that I made a similar statement near the end of Chapter VII. There I said that in order to produce X-rays of a given wave length it was necessary to use electrons of a certain minimum energy. Now we have a statement of the same kind, only it refers to electrons of much lower energy, and to visible light, instead of X-rays.

XII

LIGHT, TOO, CONSISTS OF "ATOMS"

IN CHAPTER VII I said that the electron energy necessary to produce X-rays of a certain wave length is inversely proportional to that wave length. Thus the measurements show that in order to produce X-rays of 10^{-8} cm wave length we need electrons of at least 12,340 electron-volts (that is, we have to apply at least 12,340 volts to our X-ray tube) but if we are satisfied with X-rays of a wave length of 2×10^{-8} cm we need only 6170 volts. Now if this rule holds strictly we can calculate from these X-ray measurements what energy electrons must have to produce the yellow sodium light. Its wave length as we saw on page 38 is 5.9×10^{-5} cm, or 5900 times longer than 10^{-8} cm, hence the electron energy required to produce it should be 5900 times smaller than the 12,340 electron-volts needed to produce X-rays of 10^{-8} cm wave length. If you work that out you find exactly the 2.1 electron-volts which are needed, according to direct experimental evidence, to make sodium atoms emit their characteristic yellow light.

Now if it is impossible to produce light of a certain kind except by supplying a certain minimum amount of energy, this must mean that light itself cannot occur in arbitrarily small amounts but consists of parcels containing a finite amount of energy; namely, just the energy required to produce the light in question. We are thus forced to

assume that light,¹ in a sense, consists of atoms that are commonly called *light quanta* or *photons*. Their existence forms part of the basis of that great body of knowledge encompassed by the term "Quantum Theory."

The energy contained in a photon depends, as we have seen, on the wave length of the radiation, being inversely proportional to it; we can put this differently by stating that the energy of a photon is proportional to the frequency of the radiation. In the latter form this statement is perhaps more easily remembered, and we shall now make it quantitative by translating all the quantities into absolute units. The frequency of an electromagnetic wave is found by dividing the speed of the wave (that is, the speed of light, 3×10^{10} cm/sec) by the wave length;² hence for X-rays of 10^{-8} cm wave length the frequency is 3×10^{10} cm/sec divided by 10^{-8} cm, or 3×10^{18} oscillations per second. To produce such X-rays we need electrons of an energy of at least 12,340 electron-volts. In absolute units such electrons have an energy of 1.98×10^{-8} erg each, and this must therefore be the energy of a single photon of radiation (X-rays) with a frequency of 3×10^{18} . Since the energy of the photon is proportional to the frequency of the radiation there exists a universal constant which, if multiplied by the frequency, gives us the energy of the photon. We can calculate this constant from our figures and find 1.98×10^{-8} divided by 3×10^{18} which gives 6.6×10^{-27} .

This constant was first calculated by the German Max

¹ The physicist often uses the term "light" in a loose way, applying it not only to visible rays but also to infrared and ultraviolet rays, and even to X-rays.

² This can be easily seen. In one second the wave travels 3×10^{10} cms. If we divide this distance by the length of a single wave we obtain the total number of wave crests over this distance, which is the same as the number of wave crests which travel past a given point in one second. This number, however, is nothing but the frequency of the wave.

Planck (in 1900, by an entirely different and rather complicated argument) and is therefore commonly called *Planck's constant*. Before 1900 nobody even suspected that light—like matter and electricity—consisted of smallest units, and the Nobel Prize which was awarded Planck seems an almost puny reward for an achievement which influenced the course of science as much as Columbus' journey in 1492 influenced the course of history.

We have seen that in order to produce light of a certain wave length we must invest at least a certain minimum amount of energy. What if this light strikes a body and becomes absorbed? Does the energy which we invested reappear? In general one would expect that the energy is converted into heat as the light gets absorbed, just as the kinetic energy of a falling stone is converted into heat when the stone strikes the ground. This is indeed nearly always true. When you warm your hands in front of a fire you profit from those millions and millions of light quanta (mostly in the infrared part of the spectrum) which are emitted by the flames and the glowing cinders and some of which are absorbed in your hands where their energy gets converted into heat. However, the amount of heat produced by a single photon (light quantum) is far too small to be detected by the most sensitive thermometer.

There are cases where not all the energy of the absorbed light is converted into heat. If light strikes a photographic plate, some of its energy is used in producing certain chemical changes, mainly the decomposition of some of the silver bromide contained in the photographic emulsion. To decompose a single molecule of silver bromide requires a certain amount of energy, and light quanta which carry less than this amount of energy cannot decompose the molecule. This explains the fact (which I mentioned on page

40) that infrared light of too great a wave length does not affect the photographic plate; its quanta do not carry enough energy to enable one of them to decompose a silver bromide molecule. It is of course possible that two photons hit the same molecule at the same time and, by their united effort, succeed in decomposing it. But it is easy to calculate that such an event will happen very rarely, even if the light is very intense, that is, if the photons strike the plate at a very great rate. And if two quanta strike the same molecule one after the other, the energy supplied by the first quantum will have been dissipated as heat before the second quantum arrives unless the second quantum arrives within a very short time (much less than a billionth of a second) after the first one.

Thus the behavior of the photographic plate, in particular the fact that the plate is insensitive to light above a certain wave length, supports our previous conclusion that light consists of quanta, and that the energy of a single quantum is smaller for longer waves. Evidence of a much more definite and precise character can be obtained from a study of the so-called photoelectric effect, which forms the basis of those light-sensitive cells (photocells) which have found so many applications in modern electronic engineering.

A photocell of the kind which shows the phenomenon most clearly consists of an evacuated glass container in which there are two electrodes (see Fig. 16). One electrode is a wire grid which allows the light to fall on the other electrode, a plate which is covered with a thin layer of cesium.¹ This cell behaves in a manner quite analogous to the lamp with which Edison discovered the emission of electrons from hot metals (see page 92). As long as the

¹ Cesium is an element, one of the alkali metals, to which sodium also belongs. You will hear more about the alkali metals in Chapter XVI.

cell is kept in the dark no current will pass between the two electrodes. But as soon as light is allowed to fall on the plate with the cesium layer, electrons are given off which can be drawn to the grid electrode if the latter is made positive with respect to the cesium electrode.

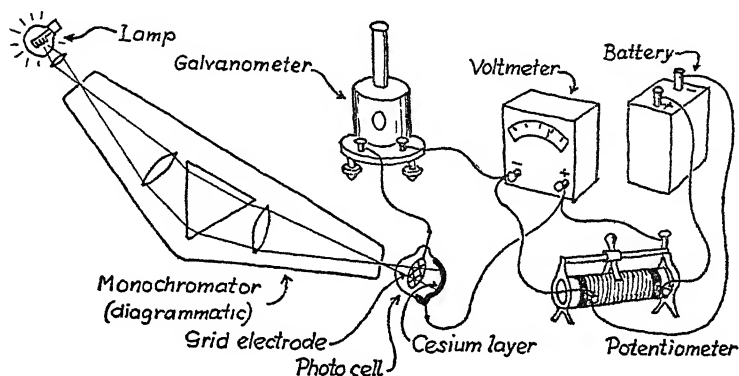


FIG. 16. Measurement of Planck's constant through study of the photoelectric effect. Light is passed through a monochromator (essentially a spectrograph—see Fig. 8—with an exit slit instead of a photographic plate) and then falls on a photocell. By adjusting the rheostat one can find the voltage (measured by the voltmeter) at which the electrons liberated from the cesium layer by the action of the light are just prevented from reaching the grid electrode. The galvanometer serves to indicate whether any electrons are passing through the photocell. For interpretation of these measurements, see text.

Such a cell resembles a photographic plate in that it responds only to light with a sufficiently short wave length. If the wave length is increased above a certain amount, no more electrons are given off. This limiting wave length depends on the material of the electron-emitting plate; cesium has a particularly long limiting wave length and is therefore used in preference to other metals. The reason for the existence of such a limiting wave length is that a certain

energy is required to pull an electron out of the metal,¹ and that light with longer waves consists of quanta which do not have enough energy.

Now what happens if light with appreciably shorter waves falls on our cesium layer? In this case only part of the energy of the photon is used up in pulling the electron out of the metal; what happens to the remainder? Well, you know what happens when you pick up a heavy-looking suitcase only to discover that it is empty; the case comes off the ground at great speed and everybody laughs. Your excess energy was employed in giving kinetic energy to the case, and that is just what happens when an electron is pulled out by a quantum which carries more energy than is necessary for removing the electron; the excess energy is used in giving kinetic energy to the electron.

If the electrons are emitted from the cesium layer with a certain speed they should be able to get over to the grid electrode "under their own steam" even if there is no electric field to pull them across. Indeed, they should be able to get across even if there is a small electric field opposing their motion, just as a ball can climb a hill if it is rolled along at sufficient speed. If one gradually increases this opposing field one comes to a point when the electric current ceases, that is, when the electrons are just no longer able to run up the "hill" to the grid electrode. If at this point the potential difference between the cesium layer and the grid electrode is two volts, for instance, this means that the electrons are thrown out from the cesium layer with a kinetic energy of two electron-volts, since such an energy

¹ This is why electrons normally (at ordinary temperatures) stay inside the metal and can be conveyed through mile-long wires without leakage. If the metal is made hot the heat motion of the electrons becomes more vigorous, and at sufficiently high temperatures some electrons get enough energy to escape from the wire, as we saw on page 94.

will barely enable them to run up against a potential difference of two volts.

By carrying out such measurements with light of various wave lengths one finds that the electrons behave just as quantum theory leads one to expect. If light near the limiting wave length is used the electrons come out of the metal with very low speed and a very small opposing potential is enough to stop them. If the wave length of the light is made shorter, that is, if we go from infrared through red, yellow, green and blue into the ultraviolet, the energy of the electrons given off by the cesium layer increases. If we do it in such a way that the frequency of the light increases in equal steps, the energy of the electrons increases also in equal steps, as it must since the energy of a photon is proportional to the frequency of the light. And if we divide the increase in electron energy by the increase in frequency (both measured in absolute units) we again get 6.6×10^{-27} —Planck's constant.

This experiment proves not only that light is emitted from atoms in "parcels" containing a certain energy, but also that these parcels stay together as the light spreads through space and that the energy of each parcel is all there when light gets finally absorbed somewhere. The light that comes to us from the sun has traveled over 90 million miles. Yet if we select rays of a certain wave length from it, by means of a colored glass, these rays will eject electrons from a layer of cesium in a photocell and impart to them the same speed as if they had been selected, by means of the same colored glass, from the light of a lamp a few inches away. While the light from the sun spreads in all directions and gets weaker and weaker as the distance increases, the individual light quanta travel through space like

little bullets, losing none of their energy even though they travel millions of miles.

We are thus faced with a very peculiar situation. On the one hand there exists an overwhelming body of evidence that light consists of electromagnetic waves. Electromagnetic waves spread in all directions through space and get weaker and weaker as the distance from their source increases. Hence the energy conveyed by these waves becomes more and more diluted. On the other hand, there is an equally convincing body of experiments (of which I have mentioned only a few) which tells us that light consists of little bullets (called quanta or photons) which appear to be indivisible and retain their energy however far they travel through space. Hence the physicist appears to be in the awkward position of a judge who is called upon to settle a quarrel between two parties each of whom has an equally convincing case and an equally large crowd of trustworthy witnesses.

There was a legendary judge who tried to extricate himself by saying that both parties were right. Despite the ridicule which this judge received, the physicist of today takes a similar attitude in the case "waves vs. quanta." He says that some features of light can best be explained by saying that light consists of electromagnetic waves, while other features fit in with the assumption that light consists of separate indivisible quanta. And if you ask, "But what is light really?" he may startle you with the counter-question, "What do you mean by 'really'?"

Let me give you a very crude example. If you came into your living room one morning and found a weird animal there which had the appearance of a cat if you look at it with your left eye, but looked like a dog if you use your right eye, you would probably think at first that one of your

eyes must be deceiving you. But if that animal continued to live in your house for years and if all your visitors saw it, too (in the same ambiguous fashion), you would probably get used to it; and in time the question, "What is it really, a cat or a dog?" would appear meaningless to you. You would probably answer, "It is a cat for my left eye and a dog for my right eye, so what do you mean by 'really'?"

Nobody has ever seen such an animal (so far as I know) and therefore this attitude appears very strange to most people. Yet it is shared by a large number of physicists, and its main protagonist is the Danish physicist, Niels Bohr, whom many of his colleagues regard as one of the profoundest thinkers of our time. He says that light has two complementary aspects, the wave aspect and the particle aspect, of which one or the other comes to the fore, depending on the kind of experiment we are doing. The word "complementary" is used to indicate that the two aspects never appear both at once in such a way that they would come into conflict with each other.¹ Bohr thinks that this idea of "complementarity" is a reasonable extension of the simpler idea of "reality" which has been found to be too narrow to interpret some of the results of modern physics. He also thinks that the idea of complementarity may be the key to certain difficulties in other fields of human thought, for instance, in connection with questions regarding the freedom of will. These are philosophical questions and I am not competent to talk about them; I merely wanted to tell you a little about Bohr's ideas since they have a direct bearing on the work of the atomic physicist, and I hope Bohr will forgive me the coarse and super-

¹ In our cat-and-dog analogy that would mean that you (and all your visitors) could never open both eyes at the same time. But the analogy is really too crude to allow much elaboration.

ficial presentation which I have given his profound and subtle thoughts.

If you still feel unsatisfied by what I have just said (as you probably do) I should like you to keep two things in mind. First of all, both the wave aspect and the quantum aspect of light are based on a large number of experimental facts, and some of the best brains among physicists have tried hard for a number of years to interpret these facts in a different way, so as to make all of them agree either with the wave picture or with the quantum picture. All these attempts—some very ingenious—were unsuccessful. Secondly, all new thoughts in science appear strange at first, and it takes a long time before people get used to them. When scientists first discovered that the earth was round, nearly everybody refused to believe that there could be people on the other side who presumably spent all their lives upside down. It took a long time before people were reconciled to this doctrine, which nowadays is taught in elementary schools and, as a result, is universally accepted. Similarly, Einstein's Theory of Relativity was at first attacked from many sides; now, forty years later, it forms part of the established body of physical science and all controversy about it has ceased, even though it has not yet become part of general education as it probably will in time. The idea of complementarity is only about twenty years old and, so far as I can see, is gaining ground steadily among physicists. Maybe in a century it will be taught in elementary schools and people will accept as a matter of fact that light is an electromagnetic wave or a spray of photons, depending on how you look at it.

XIII

SOME ELEMENTS ARE REALLY MIXTURES

LET US go back again and review the methods for determining the weight of atoms and electrons. We have discussed four such methods. In the first one (Chapter II) we actually count the atoms in a known weight of polonium, making use of the peculiar property of polonium that each of its atoms produces one and only one light flash if mixed with zinc sulphide. In the second method (Chapter VI) we determine, with the help of X-rays, the spacing of the atoms in a crystal of sodium chloride; from this we can calculate the number of atoms in a crystal of given size and therefrom, after weighing the crystal, the weight of a single molecule of sodium chloride. The third method (Chapter VIII) depends on the assumption that in a solution of a silver salt the silver ions (electrically charged silver atoms) all carry the same charge, and that this charge is known from Millikan's oil drop experiment. One can then calculate how many silver atoms will be deposited by a given current in a given time, and by dividing the weight of the deposit by the number of silver atoms obtain the weight of a single atom. The fourth method (Chapter XI) was used to determine the weight of an electron. Here we used an evacuated container in which we produce a beam of electrons, all traveling in the same direction and at the same speed; we then measure how much this beam gets deflected

in a certain magnetic field, and from this we can calculate the mass of the electrons.

The first three methods, different as they are, are similar in one respect. In all three, we somehow determine the number of atoms in a sample of known weight. This sample must be big enough so that it can be weighed, that is, it must contain a very large number of atoms. The same is true of those measurements by which the chemists have found how many times heavier the atoms of one element are than those of another. From all the evidence I have thus far presented we cannot conclude that all the atoms of a given element have the same weight; all we have measured so far is their average weight. The chemist tells us that the average silver atom weighs 108 times as much as the average hydrogen atom; but how do we know that silver is not a half-and-half mixture of two kinds of silver atoms which weigh, respectively, 107 and 109 times as much as the average hydrogen atom? And can we be sure that all hydrogen atoms are alike?

Well, there is one thing of which we can be sure. All electrons have the same weight. In our discussion of the way in which the mass of the electron can be determined from the magnetic deflection of a beam of electrons, we noted that if our beam contained several kinds of electrons differing in weight, these electrons would describe circles of different size in the magnetic field and the points where these circles strike the screen would be marked as several luminous spots. Actually, one finds only one luminous spot, and from this we conclude that the electrons in our beam all have the same weight.

You have probably guessed by now what I am driving at. Our next step must be to measure the weights of atoms through the magnetic deflection method.

For this we can use an apparatus similar to the one used to deflect electrons (Fig. 15), with a few changes. First, we must replace the electron gun by an ion gun.¹ Secondly, we must change the direction of the magnetic field. While the electrons are negatively charged the ions we now wish to investigate have a positive charge² and would be deflected away from the screen instead of toward it if we did not change the direction of the magnetic field. Finally we must make the magnetic field much stronger because ions are much heavier than electrons and therefore much harder to deflect. For this we use an electromagnet which has a heavy coil of wire through which we can send a strong electric current.

Let us start by putting hydrogen into our ion gun so that it produces a beam of hydrogen ions. No luminous spot is visible on the screen; perhaps our magnetic field is too weak. Let us raise the current through the magnet coil in order to increase the magnetic field. Ah, here it comes, a spot of green light right at the edge of the screen. Are there more to come? We had better keep on increasing the magnetic field slowly and watch the screen. Our spot moves slowly toward the ion gun as the increasing magnetic field forces the ions to describe smaller and smaller semi-circles. Here comes another spot! And here a third one! Are our worst suspicions coming true, and is hydrogen a mixture of several kinds of atoms? Let us watch the screen a little longer, increasing the magnetic field all the time.

¹ In an ion gun, ions are produced by breaking up gas molecules with the help of fast electrons, a process mentioned in Chapter XI. I shall give a more detailed description of an ion gun in Chapter XVIII.

² Because the atom which is hit by a fast electron loses one of its own electrons. However, occasionally it happens that the fast electron sticks to the atom which it hits and then we get an atom with an additional electron, that is, a negative ion; but this happens fairly seldom.

Well, there seem to be only three spots; we have now made the field so strong that they are crowded quite close to the ion gun, and no other spots are visible anywhere on the screen. So it seems that our ion gun gives out three different kinds of ions.

Let us now figure how much these different ions weigh. Our magnet is calibrated so that we can tell the intensity of the magnetic field simply by reading the ammeter which indicates the current through the magnet coil. There is, too, a scale engraved on our screen, which lets us tell at a glance how far a particular spot is from the ion gun or, in other words, gives the diameter of the semicircle on which these particular ions are running. From these data, the magnetic field intensity and the diameter of the circular path (in conjunction, of course, with the kinetic energy of the ions, which is determined by the voltage on the ion gun) we can calculate the mass of those ions which produce a particular spot on the screen.

If we start with those ions which form the spot nearest to the ion gun and which must therefore be the lightest of the lot, we find that they weigh exactly what we had previously found—by our first three methods—as the weight of an average hydrogen atom. Now that is puzzling. Surely, if hydrogen is a mixture of several kinds of atoms, then the lightest of them must weigh less than the average. The second spot, we find, is made by ions which weigh just twice as much as an average hydrogen atom, and the third spot by ions which weigh three times as much. Now what does all this mean?

The explanation is very simple. All hydrogen atoms weigh the same.¹ Only the first spot is made by “atomic ions,”

¹ Actually, about one in 5000 hydrogen atoms is heavier, as we shall see later. But these would not show up in our present crude setup.

that is, by electrically charged single hydrogen atoms. The other two are made by "molecular ions," that is, by electrically charged molecules each of which consists of two or three hydrogen atoms.

You see how everything falls into place. The agreement between the mass of the lightest ion and the previously determined mass of a hydrogen atom is no longer puzzling but, indeed, a matter for rejoicing, since it confirms our earlier measurements and furthermore shows that these measurements give the true weight of a single hydrogen atom (and not merely an average of several different kinds of hydrogen atoms). The fact that the other two kinds of ions are exactly two and three times heavier is not accidental but an obvious consequence of the fact that those ions are clusters of two or three atoms. It is also fairly easy to form a picture of how these ions are produced. Ordinary hydrogen gas consists of molecules each made of two hydrogen atoms. In the ion gun these molecules are bombarded with fast electrons. Sometimes such an electron will break the molecule into its two atoms and also tear loose an electron from one of them; in this way an atomic ion (a charged hydrogen atom) is formed. Sometimes the impinging electron merely removes an electron from the molecule but leaves the latter otherwise intact; in this case we get a molecular ion which weighs as much as two atoms.¹ Ions of three times the mass of a single atom can be formed, for instance, if an atomic ion attaches itself to an ordinary hydrogen molecule. Probably even larger clusters are formed occasionally, but they are presumably so unstable that they fall to pieces again before having time to complete their

¹ Actually, it is of course lighter by the weight of one electron; however, the electron is so light ($1/1830$ of a hydrogen atom, you remember) that the difference cannot be measured in practice.

semicircular path; therefore they cannot form luminous spots on the screen.

Hydrogen is the element with the lightest atoms; the one next to it is helium, a gas which is obtained commercially from the so-called natural gas which comes out of the ground in or near oil fields. Helium is one of the "noble" gases (four others are called neon, argon, krypton and xenon) which are called noble because they refuse to associate themselves in chemical compounds with other elements, or even with each other. In other words, their atoms do not combine with each other or with other atoms to form molecules, but always remain single. Since helium is much lighter than air and non-inflammable (to burn means to form a compound with oxygen, with the production of heat) it is used for filling airships.

Let us now see what we get if we put helium, instead of hydrogen into our ion gun. Two luminous spots promptly appear on our screen, and from their position we can compute the ions which produce the spots to be respectively two and four times heavier than a hydrogen atom. Now the "mass 4" spot is all right, for we know that the atomic weight of helium is 4; that its atoms are just four times heavier than hydrogen atoms. But how does the "mass 2" spot come about? Have we by any chance succeeded in chopping some of the helium atoms in half? Nothing so drastic; we have merely succeeded in knocking two electrons off some of the helium atoms, thus producing ions which carry twice as big a charge as the others. Now if an ion carries a double charge it behaves, both inside the ion gun where it gathers speed and in the magnetic field where it gets deflected, exactly like a pair of ions, each of which has half the mass and just one single charge. But then a pair of identical ions follows of course the same path that each

one of them would follow if it were all by itself. Hence our doubly-charged ions land at the same spot as if they had only a single charge and half their real mass, and this explains the apparent "mass 2" spot.

How do we know that this explanation is correct? Here is a simple test which will at least make it very plausible. Obviously we must hit a helium atom pretty hard in order to tear off two of its electrons at once. Perhaps we can avoid doing it by using slower electrons for ionizing the helium in our ion gun. Let us gradually reduce the potential by which the electrons inside our ion gun are being accelerated. For a while nothing happens, but now you see that the "mass 2" spot is rapidly getting weaker and if I lower the potential a little more it disappears altogether. At the point where the spot just about disappears the potential is roughly 80 volts; if we lower the potential further the "mass 4" spot remains unaffected until we get down to about 25 volts; at this point the "mass 4" spot, too, disappears and now our ion gun produces no more ions.

According to this experiment it takes an energy of about 25 electron-volts to remove one electron from a helium atom, but about 80 electron-volts to remove two. You might have expected that it would take just twice as much energy to remove two electrons as is needed to remove one, but you must remember that after one electron is removed the remaining ion has a positive charge and therefore offers a much more spirited resistance to the removal of a second electron. For this reason one would expect the removal of three electrons to be even more difficult, but possible with sufficiently fast electrons, with an energy of perhaps 200 or 300 electron-volts.

This guess, however, is wrong. Even if you bombard helium with electrons of many thousand electron-volts you

never find helium ions with more than two positive charges or, in other words, helium atoms which have lost more than two electrons. This stubborn refusal to give up more than two electrons has only one sensible explanation: the helium atom contains only two electrons; "the guy really can't pay more."

How about hydrogen? There we got only ions with a single charge; perhaps the energy of the bombarding electrons was too low? No, it wasn't. You can bombard hydrogen with fast electrons all you wish; you will never get atoms which have lost more than one electron. The conclusion is that the hydrogen atom contains only one electron.

Let us think for a moment. The hydrogen atom, the lightest of all, contains only one electron; the helium atom, the next in weight, contains two. The next element, in order of increasing atomic weight, is lithium. Will the lithium atom contain three electrons?

Lithium is not a gas, but a metal; it is silver-white, soft, and tarnishes quickly. Fortunately it can be easily vaporized at a moderate temperature (red heat) and it is not very difficult to rebuild our ion gun so that we can introduce lithium vapor into it. This time we will be cautious and slowly increase the energy of the electrons which serve to ionize the lithium vapor until the first spot appears, made by singly-charged ions; by further increasing the potential we eventually get a second spot, corresponding to doubly-charged ions, and perhaps, if our guess was right, a third one. We know the atomic weight of lithium—it is 6.9—so we know where to expect the first spot.

Now what's this? There are two spots showing up at once! They are quite close together, at about the expected position. A short calculation shows that they are made by

ions which are respectively 6 and 7 times heavier than hydrogen atoms; and the "mass 7" spot is much brighter than the "mass 6" spot. So here at last we seem to have found an element which is a mixture of two kinds of atoms, those of atomic weight 7 being more frequent than those of atomic weight 6. Such a mixture would of course have an average atomic weight a little under 7, and that is just what chemistry tells us.

Let us go on increasing the electron energy. Here come two more spots! Their position would seem to indicate ions of the atomic weights 3 and 3.5, but of course we expected them just there and know that they are doubly-charged ions of atomic weight 6 and 7. And here are two more, exactly at the positions expected for ions carrying a triple charge. After that we get no more spots, however much we increase the energy of the ionizing electrons. Our guess was right: the lithium atom contains three electrons.

So there are indeed elements which are a mixture of two different kinds of atoms. The difference in weight is quite appreciable; but otherwise the two kinds of atoms appear to be very similar. Their chemical properties must be the same or else the chemists would have discovered long ago that lithium is a mixture of two substances. And we have just seen that the two spots on our screen always appear together as we raise the electron energy; this means that the two kinds of atoms presumably have their electrons arranged in the same fashion. In both of them, the first electron comes off rather easily; it takes only 5 electron-volts to knock it off. But the other two are held much more firmly; it takes no less than 75 electron-volts to tear off two electrons, and 122 electron-votes to remove all three.

If indeed chemical forces (that is, those forces of at-

traction holding the atoms together in molecules) are essentially electrical in nature, then it is plausible to assume that the chemical properties of an element are determined by the way in which the electrons are arranged in its atoms. The fact that the two kinds of lithium atoms have the same chemical properties is then a necessary consequence of the similar arrangement of electrons in the two kinds of atoms. We can even go so far as to define an element as a substance in which all the atoms have the same arrangement of electrons. This definition may sound strange and impractical to you, since it is much easier to do chemical tests than to investigate the arrangement of electrons. Yet I think this definition has some advantages. The usual chemical definition of an element is essentially negative; it defines an element as a substance which the chemists, despite numerous attempts, have not been able to decompose. How do we know that they will not succeed one day? Actually, after it was discovered that some elements are mixtures of several kinds of atom, chemists made great efforts to separate these mixtures, and in some cases they succeeded in doing so. Should we then say that lithium is no longer an element? Strictly speaking, we should. However, the chemical differences between the two kinds of lithium atoms are so minute, so much smaller than the differences between any two different elements (in the traditional sense) that it would be silly to call lithium a mixture of two different elements.

We shall therefore use the following definitions. Atoms with the same arrangement of electrons are said to belong to the same element. Atoms with the same arrangement of electrons, but with different weight, are said to belong to different "isotopes" of the same element. Lithium has two

isotopes, of atomic weights 6 and 7; helium has only one,¹ of atomic weight 4. Some elements have more than two isotopes; the record is held by tin, which is a mixture of no less than ten isotopes. Incidentally, silver is indeed—as I suggested a few pages ago—a half-and-half mixture of two isotopes, with the atomic weights 107 and 109. One isotope of which you have probably heard is the famous “uranium 235,” the isotope of atomic weight 235 of the metal uranium of which it forms only a small fraction (more than 99 per cent of uranium consists of an isotope with the atomic weight 238). This small fraction is very important, however, since its special properties enable it to be used for making atomic bombs.

¹ “Isotopes” means “occupants of the same place” (from two Greek roots which mean “same” and “place”). Some people think that the word isotope—like the word brother—should be used only when there are at least two. However, this ruling leads to clumsiness, and the physicists, practical people and habitual disregards of the finer points of etymology, tend to ignore it.

XIV

RADIOACTIVE ATOMS

LET US go all the way back to Chapter II. There I told you about an element called polonium which had most peculiar properties. If you mixed a minute amount of it with some zinc sulphide and looked at the mixture through a magnifying glass, in a dark room, you would see numerous little light flashes, like sparks. More, each flash was caused by a single polonium atom, which, after having produced a flash, could never produce another one. How does polonium come to have these peculiar properties?

We shall carry out a few simple experiments. In the first place, instead of mixing the polonium with the zinc sulphide, we shall place the one at some distance from the other and see what happens. We prepare a zinc sulphide screen by spreading a thin layer of the stuff on a glass plate. We had better make sure the material has not been accidentally contaminated by a trace of polonium or some similar substance; this we do by taking the screen to a dark room and watching it for a minute or two through a magnifying glass, verifying that there are no light flashes visible. Next we want a minute sample of polonium. I have a fairly big amount in my laboratory; if I just touch it with a needle enough will stick to the point to serve our purpose. All we need in addition to this needle, the zinc sulphide and the magnifying glass, is a piece of sealing wax, some matches, and two empty matchboxes.

Figure 17 shows our completed setup. The needle with the polonium has been waxed onto one matchbox, the screen and the magnifier onto the other. The two boxes have been placed on the table in such a way that the needle-point almost touches the zinc sulphide screen. Now we turn off the lights and look at the screen through the magnifier. There is a merry crowd of little sparks around where the needle-point is, with an occasional one farther away. Thus we see, it is not essential that the polonium and the zinc sulphide actually be mixed; the polonium appears to be sending out some kind of "radiation" which causes flashes when it hits the zinc sulphide.

How far does this radiation travel? We can at once answer this question by moving the two matchboxes apart so that the distance between the polonium and the screen is increased. Our little crowd of sparks spreads out and becomes less dense, but they keep flashing with undiminished vigor until the needle-point is about an inch from the screen. After that, it is noticeable that the flashes are getting weaker; when the needle reaches a distance of one and a half inches from the screen they disappear. So the rays which cause the flashes can only travel about an inch and a half; after that they have spent their power. Perhaps we had better call them from now on by their usual name, alpha rays.

Let us push the needle close to the screen again and investigate the power of our alpha rays to penetrate various materials. A piece of window glass, inserted between the needle-point and the screen, makes the flashes disappear; so does thin metal sheeting, or even a piece of paper. However, cellophane lets the alpha rays through, and so does very thin aluminum foil. Two layers of cellophane are al-

ready too much.¹ So our alpha rays can penetrate layers of solid material, provided they are thin enough; measurements have been made on all kinds of material to find the maximum thickness which the alpha rays of polonium can penetrate.

Do the alpha rays travel in a straight line? This question, too, can be answered very quickly, at least approximately. We move our needle back a distance of $1\frac{1}{4}$ inches from the screen (that is, as far as we can go before the flashes become too weak) and place a piece of paper with a small hole in it halfway between the needle-point and the screen. After we have done this we find but few flashes, and all of them practically at the same spot, just where we would expect the rays to hit the screen if they travel in a straight line from the needle-point through the hole in the paper. Occasionally we see a flash some little distance away from where it should be. So our answer is: Most of the alpha rays travel in a straight line, but a few deviate slightly from the straight path. We shall see later that those few that deviate are of great interest to the atomic physicist.

We can do another important test with this setup. We fetch a horseshoe magnet and place it so that the alpha rays have to pass between its poles, on their way from the needle-point to the small hole in the paper. Careful observation of the screen indicates that the spot where most of the flashes occur has shifted a tiny bit to one side. This shows that the alpha rays have been slightly deflected in the strong magnetic field between the poles of the magnet. Now you remember from the last chapter that particles which carry an electric charge get deflected in a magnetic field, and that the direction in which they get deflected

¹ If each layer is about one thousandth of an inch thick; some commercial cellophanes are thinner than that.

depends on whether they are positively or negatively charged. From the direction in which our alpha rays get deflected we can conclude that they consist of particles which carry a positive charge. The fact that they get only very slightly deflected (much less than the various ions in the experiments which I described in the last chapter) must mean that they are either very heavy or very fast.

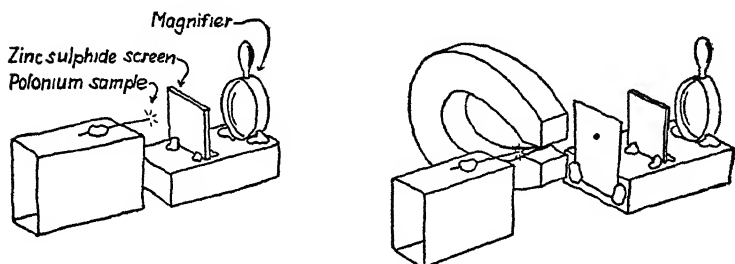


FIG. 17. Left: A polonium sample mounted on a matchbox emits alpha particles which produce light flashes (scintillations) on a zinc sulphide screen, the flashes are observed through a magnifying lens. Right: The arrangement has been supplemented by a sheet of paper with a small hole through which only a narrow beam of alpha particles can reach the screen. A horseshoe magnet is placed so that the alpha particles pass between its poles, in doing so they are slightly deflected, and those which go through the hole no longer strike the screen in exactly the same place as in the absence of the magnet

Let us just recapitulate what we have learned from our sealing-wax-and-matchbox arrangement. Polonium sends out positively charged particles (alpha particles) which produce visible light flashes on striking zinc sulphide. These particles travel about $1\frac{1}{2}$ inches in air, and most of them travel in straight lines although some of them suffer slight deviations. Quite a lot of information really, from such primitive equipment!

If we want to get more accurate information we must

use somewhat more elaborate instruments. In particular, the short range of the particles is annoying; it would be much easier to measure, for instance, their deflection in a magnetic field if they had a range of a foot or more. Fortunately that can easily be arranged; all we have to do is to put our entire setup into an airtight container and pump out the air. If we pump out half the air the range of the alpha particles will be found to have doubled; with a very primitive pump we can remove 99 per cent of the air and then our alpha rays will have a range of over ten feet, which is ample.

With the help of such an evacuated container and a large magnet it is easy to measure the deflection of the alpha particles. Unfortunately this does not yet tell us their mass, because we do not know their speed. In order to calculate both their mass and speed we have to make a second measurement; we have to measure how much they are deflected in an electric (rather than magnetic) field. For this there must be two plates in our container and provisions for connecting them to a source of electric potential, similar to the arrangement we had in the television tube shown in Fig. 14. Once we have measured the deflection of the alpha particles both in magnetic and electric fields we can calculate their speed and their mass.

The results are as follows. The speed turns out to be 1.6×10^9 cm/sec, about one-twentieth of the speed of light; rather fast by ordinary human standards, but quite reasonable to an atomic physicist. The mass is a bit surprising; it appears to be twice that of a hydrogen atom, but we know from the last chapter that it may also be four times the hydrogen mass if the particles carry a double charge (if they are atoms which have lost two electrons). How are we going to find out?

The most direct way to find out is through the following, rather tricky, experiment. First we make a beam of alpha particles with the help of a small polonium sample and a plate with a hole in it (just like the arrangement by which we ascertained that alpha rays travel in straight lines). By means of a zinc sulphide screen we count how many alpha particles are coming through the hole every second. Then we transfer the whole arrangement—polonium sample and plate with hole—into an evacuated container in which there is a hollow metal sphere, placed so that the beam of alpha particles can enter through a hole in the sphere. Each alpha particle, as it enters the sphere, brings its charge along, and as a result the sphere gradually gets charged. A delicate electrical instrument is connected to the sphere and allows us to measure the amount of charge which the sphere acquires, say, in ten minutes. Since we know how

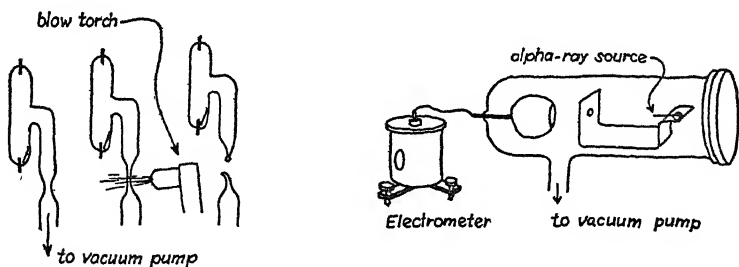


FIG. 18. Left: A glass tube (perhaps two inches long) containing some polonium is connected to a vacuum pump and carefully evacuated. Then a previously constricted portion of the connecting tube is heated and thereby softened, with the help of a blowtorch; by pulling gently, the tube is severed from the pump and, at the same time, sealed off airtight. Although empty immediately after being sealed off, the tube soon is found to contain some helium, in amounts growing from day to day; this comes from the polonium. Right: Apparatus for measuring the amount of charge carried by alpha particles. A beam of alpha rays enters a hollow sphere inside an evacuated container; the accumulation of electric charge on the sphere is measured by means of an electrometer.

many alpha particles are entering the sphere every second we can calculate how many particles have entered in ten minutes, multiplying by 600. From this we immediately get the charge of a single alpha particle, and it turns out to be a double charge, as we expected.¹

So the alpha particles carry a double positive charge and weigh four times as much as a hydrogen atom. We met such particles in the last chapter; they were helium atoms which had lost both their electrons. But how can helium suddenly spring from polonium, an entirely different element?

Let us make quite sure it is helium. We put a sample of polonium into a small glass tube which is connected to a powerful pump. By pumping for several hours and heating the glass tube we make sure that any air or other gas that may have stuck to the glass has been driven off and pumped away. With a glass-blower's torch we soften the glass tube which connects our tube to the pump and pull it off, making an airtight seal.²

The tube is now very well evacuated and no electric current can be forced through it even if we apply a voltage of several thousand volts to the two little wires sealed through the wall of the tube. However, if we try again after a day or two there will be a faint glow in the tube as we apply a voltage to the wires; after another few days it is possible to force enough current through the tube to produce quite a bright glow. We can analyze the light emitted by means of a spectroscope (see page 42) and the arrangement of

¹ The experiment is tricky, among other reasons, because the container must be very well evacuated. If there is some air in it, ions will be formed by collisions between the alpha particles and the air molecules, and some of these ions may drift into the sphere and alter its charge.

² The procedure just described—pumping, heating, sealing off—is essentially the same by which lamp bulbs and radio tubes are evacuated.

the spectral lines will tell us unmistakably what gas there is in the tube. And it turns out to be helium. It is possible to measure how the amount of gas in the tube increases. In this way one finds that the rate at which helium atoms accumulate in the tube is just the rate at which the polonium sample emits alpha particles. There can be no doubt any more: alpha particles are helium atoms, stripped of both their electrons.

Do you realize what this means? Just see, polonium, all on its own, does the trick the alchemists sought in vain: the transmutation of one element into another. Out of polonium, an element, comes helium, another element. Since the atomic weight of polonium is 210 while that of helium is only 4, something with the atomic weight 206 must be left over after the polonium atom has given birth to a helium atom. Lead has an isotope with the atomic weight 206, and it can indeed be shown that an atom of this lead isotope is what is left of a polonium atom after it has emitted an alpha particle.

There are a number of other elements which have this property; namely, their atoms change spontaneously into atoms of a different element. They are called radioactive elements. Some, like polonium, do it by ejecting a helium atom; some do it in a different way which I shall describe later.

Let us return to our alpha particles. We saw that they have a speed of 1.6×10^9 cm/sec. Isn't this, after all, rather fast for an atom? Let us work out the kinetic energy of such an alpha particle. We figured out on page 96 that electrons of a speed of 3×10^9 cm/sec have a kinetic energy of 2560 electron-volts. Our alpha particles are only about half as fast, so their kinetic energy would be about one-fourth (since the kinetic energy goes with the square

of the speed) of 2560 electron-volts or 730 electron-volts, if they weigh the same as electrons. But they don't; they are four times heavier than hydrogen atoms, which in turn are 1830 times heavier than electrons. Therefore their energy is $730 \times 4 \times 1830$, or about 5.3 million electron-volts! No wonder such an atom can crash through a sheet of cellophane or a foil of aluminum which consists of some 50,000 layers of closely packed atoms. On its path through air, a particle with such enormous energy will certainly break up (ionize) every molecule which it encounters, and its path will be littered with damaged molecules and atoms (that is, with ions) like the path of a hurricane.

Do you want to see the trail of broken molecules left behind by an alpha particle? Come, I shall show you the cloud chamber, the pride of the physicist. Some think that a cyclotron is a more wonderful machine, but I think the cloud chamber, small and primitive as it seems in comparison with a cyclotron, is more of a thrill, just as a boomerang which returns to its owner solely through its cunning shape and the skill of the thrower seems, to me, more thrilling than a radio-controlled pilotless plane.

Here it is, this little round glass bowl, with a waxed-on glass pane for a lid.¹ About two-thirds of it is filled with water, above the water there is air, which of course is moist, having been in contact with the water for some time. If I turn this stopcock you will see that the water level drops somewhat. Consequently, the air above the water expands slightly, thereby getting colder.² Cold air

¹ Cloud chambers have been made in a great variety of designs for all kinds of special purposes. The one I am showing you is a rather simple one.

² If air is compressed it gets hot, as you can feel when you pump up a tire. Similarly, if air is expanded it cools.

cannot hold as much moisture as warm air, and the excess moisture tends to condense into tiny droplets of water. If the air is quite clean very few droplets are formed because the water molecules have nothing to start on. If there are ions in the gas, water molecules will cluster around each ion; very soon each ion will find itself at the center of

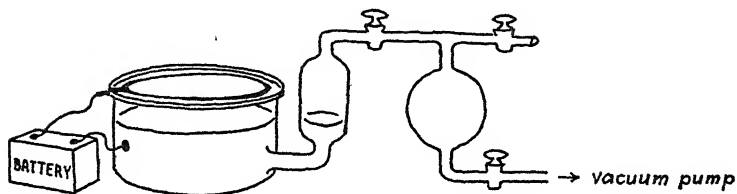


FIG. 19. A simple cloud chamber.

a water droplet big enough to be visible in a strong beam of light.

Now let us see what we get. A strong beam of light is switched on to illuminate the air inside the chamber, and a little polonium has been put in to supply alpha particles. Now you look down through the glass lid while I turn the stopcock to make the air expand. Do you see anything? Nothing but a slight fog which quickly settles to the bottom? Then we have been unlucky and no alpha particle happened to run through the moist air immediately after the expansion; the air stays cold for a fraction of a second only. Let us bring the water level back again (there is another stopcock for doing that) and wait half a minute so that the air can completely return to room temperature. You may notice that a ring of tin foil is stuck to the inside of the lid and that a thin wire goes through the wax with which the lid is stuck to the bowl, and leads to a dry battery of 90 volts, such as is used in portable radio sets; from the other pole of the battery a wire leads to the water in the

bowl. This arrangement serves to create an electric field in the chamber and the ions produced by an alpha particle are quickly pulled away, into the water or to the tin foil ring. If we did not have this electric field for sweeping out the ions they would accumulate in the chamber and spread all over it; we would merely get a heavy fog every time we made an expansion.

I think the chamber is now ready for another expansion. We can both look while I turn the stopcock. There, did you see it? A fine white streak, which almost immediately dissolves into a wisp of fog, sinks to the water surface and is gone. Obviously it is very difficult to make accurate observations on something which only lasts an instant, so for research purposes we nearly always rig up a photographic camera, with its shutter timed so that it takes a snapshot of the chamber an instant after the expansion. I have got a number of such photographs (Plate 4). Some of them show alpha particles like the one just made visible; some show other particles which I shall explain later. The white streak you saw consists of about a hundred thousand tiny water droplets, each marking the place where an ion was left behind on the tempestuous path of the alpha particle. They mark the path of the invisible alpha particle in very much the same way the path of a high-flying plane is sometimes marked by a white streak of cloud. You see that most of the particles produce streaks which are quite straight, but occasionally you find one (for instance, on Plate 5) which has a slight break.

The cloud chamber (also called expansion chamber) was invented by the Scotchman, C. T. R. Wilson, in Cambridge, England, about 1911. Hardly any other single instrument, except perhaps the cyclotron, has had so profound an effect on the development of atomic physics. "Seeing

is believing," and it is difficult to overestimate the amount of confidence which physicists have drawn from the possibility of observing with their own eyes the behavior of single atoms in rapid flight, their collisions and, occasionally, their transmutations. Most of the routine work nowadays is done by more or less automatic equipment making use of the gigantic development of electrical and electronic engineering; but when unexpected results turn up, when the usual checks and cross-checks refuse to make sense, and there seems to be no way, from the observations made, to decide between several possible interpretations, then the decision usually is: "Let's set up a cloud chamber and see what is going on here." Many an important discovery was made that way. The neutron, the positron, and the meson were first "seen" in a cloud chamber. Although we now have more efficient and rapid instruments for studying their properties, their discovery would have been greatly delayed without C. T. R. Wilson's ingenious invention.

XV

PROBING THE CORE OF THE ATOM

I SAID BEFORE that it was no wonder that an alpha particle, with its enormous energy of 5.3 million electron-volts, could crash through many thousand layers of atoms constituting a sheet of cellophane or a thin foil of aluminum. However, on second thought, it is rather astonishing. If you play billiards or pool you know that whenever your cue ball hits the other ball squarely the other ball will speed away while your cue ball practically stops. If you give your cue ball more speed this will merely make the other ball move so much faster, while your cue ball will still be stopped. Also you know that it is very difficult to graze the other ball so lightly that your own ball continues without being appreciably deflected. How then is it possible for an alpha particle to crash through several thousand layers of atoms, that is, to collide with several thousand atoms, and yet emerge with its direction practically unchanged and its speed not greatly diminished?

Of course the electrons contained in the foil do not represent a serious obstacle; they are so light that the alpha particle just kicks them aside as it goes, without being appreciably deflected. It loses a little speed every time it hits an electron, and that is why it comes to rest after having traveled through about $1\frac{1}{2}$ inches of air, or through less than two sheets of cellophane. But the electrons represent

only a very small fraction of the weight of an atom. What about the rest of the atom, the heavy part of it?

I told you before that some alpha particles suffer slight deflections on their path. Although small, these deflections are too big to be caused by a particle as light as an electron. It seems plausible that these deflections are caused by collisions between the alpha particle and the heavy part of some atom. But why are they then so rare? Why is the heavy part of an atom so hard to hit?

Put in this way, the question contains its own answer. Things are hard to hit if they are small. If the whole mass of the atom (apart from the small fraction represented by the electrons) is concentrated in a tiny core or nucleus, then it can be understood how alpha particles can penetrate several thousand layers of atoms without ever encountering one of these cores.

There is still another riddle. Why is it that an alpha particle which does collide with one of those atomic nuclei (as they are usually called) nearly always suffers only a slight deflection? You know how difficult grazing shots are in billiards; if you don't take careful aim your cue ball will either miss altogether or else be strongly deflected on colliding with the other ball. Our alpha particles are not aimed at all and yet, whenever one of them strikes a nucleus it seems to be a "grazing shot." How is this possible?

Ernest Rutherford (later Lord Rutherford), who first conceived the idea of atomic nuclei, showed that it is not only possible, but must be so. The alpha particle is a helium atom which has lost both its electrons; it is, in other words, a helium nucleus. When it approaches another atomic nucleus the fact that both of them are positively charged makes them repel each other, and the alpha particle is deflected away from the nucleus. The poorer the "aim,"

the smaller the repulsion and, therefore, the deflection (see Fig. 18). Hence to get a big deflection, the alpha particle must pass very close to an atomic nucleus, and that, of course, happens very seldom. If we know what amount of charge the atomic nucleus carries we can calculate how we would have to aim an alpha particle in order to get deflection by a definite angle. Vice versa, if we measure how many alpha particles get deflected by more than a certain angle, we can calculate how much charge the deflecting nucleus carries.

Let us recall what we learned in the last chapter about the number of electrons which an atom contains. We found that a hydrogen atom never loses more than one electron; we concluded that it only contains one electron. Hence its nucleus must carry a positive charge equivalent to the (negative) charge of the electron, since the complete atom is electrically neutral. The helium atom contains two electrons, hence its nucleus must carry two elementary positive charges. Similarly, each lithium nucleus, whether its atomic weight is 6 or 7, must carry three times the charge of a hydrogen nucleus. It would seem tempting to guess that this rule continues, and that each element has one more charge than the preceding. For instance, a nucleus of copper should have 29 elementary charges, because copper is the 29th element in the order of increasing atomic weight. This expectation was indeed confirmed by careful measurements of the deflection of alpha particles on passing through very thin copper foils, and measurements with foils of silver and platinum also agreed with the expected nuclear charge for these elements.

We now have a much clearer picture of an atom. Practically all the weight of the atom is contained in a tiny core, the atomic nucleus. This nucleus carries a positive electric

charge which is a multiple of the charge carried by the hydrogen nucleus; in other words the nucleus carries a certain number of positive elementary charges. An equal number of electrons is grouped somehow around the nucleus. Their accumulated negative charge is equal to the positive charge of the nucleus so that the whole, the atom, is electrically neutral, that is, neither positive nor negative.

Let us now try to get a somewhat clearer idea of the sizes involved. First of all, how small is the atomic nucleus? If we send alpha particles through foils of elements with a high nuclear charge (platinum, for instance, whose nucleus carries 78 elementary charges), the distribution of the deflected particles is exactly what we figure from their electrical repulsion by the nuclei. It follows that the alpha particle never actually hits a platinum nucleus but is always turned away by the electric force. Since the law of repulsion between electric charges is known we can calculate how close an alpha particle with a kinetic energy of 5.3 electron-volts can get to a nucleus with 78 positive elementary charges before being turned back. This distance turns out to be about 4×10^{-12} cm, a very small distance indeed, about 1/7000 of the distance between neighboring atoms in sodium chloride. Even at this close approach an alpha particle and a platinum nucleus do not appear to touch each other. However, if alpha particles are fired through thin aluminum foil some of them actually do collide with aluminum nuclei, as can be concluded from the fact that the distribution of those which are strongly deflected no longer agrees with what one figures from the electric repulsion. This is not very surprising, since the aluminum nucleus has only 13 elementary charges, one-sixth of the charge of a platinum nucleus, and the alpha particles can therefore get six times closer. From numerous measure-

ments of this kind we conclude that atomic nuclei have a diameter of about 10^{-12} cm, or a millionth of a millionth of a centimeter. I shall later describe a much simpler and more accurate method for measuring the diameters of atomic nuclei.

Next we ask, at what distance from the nucleus are the electrons? There are several ways of answering this question, and the answers do not agree very well. This is not surprising, for the electrons are presumably not all at the same distance. The outermost ones cannot be much farther away than about 10^{-8} cm, one hundred-millionth of a centimeter, which is about half the distance between neighboring atoms in most solid bodies. Another estimate can be derived from the known amount of energy needed to remove one of the electrons. We know for instance that it takes 13.5 electron-volts to remove the electron from a hydrogen atom; if the electron were located more than 10^{-8} cm from the nucleus, it would not take that much energy to overcome the attractive force of the nucleus. On the other hand, if the electron were much closer to the nucleus it would be much harder to remove. Other experiments indicate that some of the electrons are much closer to the nucleus.

Let us stick to the hydrogen atom for a moment. After all, the nucleus and the electron attract each other. What keeps the electron at a distance several thousand times greater than the size of the nucleus? In other words, why doesn't the electron fall onto the nucleus? The explanation which comes immediately to the mind of the physicist is this: the electron does not fall onto the nucleus for the same reason that the moon does not fall on the earth. The moon goes round the earth in a circle, and the "centrifugal force" of its motion just balances the attraction between earth and moon. Or to put it differently, the moon

would run away in a straight line if it were not for the attraction by the earth which forces the moon to go round the earth in a circle. In the same way the earth is forced to go round the sun in a circle (to be precise, in a nearly circular ellipse), just as the other planets of our solar system.

However, this explanation meets with great difficulties. Unlike the earth or the moon, the electron has an electrical charge. If an electrically charged body runs round and round in a circle, it must act like a transmitting aerial and it must emit electromagnetic waves. These waves represent a steady drain of energy to the electron, which therefore continually loses energy. As its energy, and therefore its speed, diminishes, the attraction of the nucleus forces the electron into a smaller and smaller orbit. All this can be calculated from electromagnetic theory. The electron must spiral closer and closer to the nucleus until the two are in contact, and the whole process should take only a small fraction of a second.

Even if one could think of a reason for the electron not emitting electromagnetic waves, there are still other difficulties. The electron would then continue to run on the same circle indefinitely, but only as long as there is nothing to disturb it. However, that is far from being the case. Any collision with another atom (and they happen millions of times a second) will disturb the orbit of the electron, and as a rule after this disturbance the electron will run in a circle (or an ellipse) of different size. If the electron is torn off altogether, as, for instance, by the impact of an alpha particle, the nucleus soon catches a new electron. But one sees no reason why this new electron should move in the same orbit as the old one. We might expect the hydrogen atoms to be a motley lot, with their electrons running in orbits of all shapes and sizes.

Actually hydrogen atoms are very much alike, much more closely than wineglasses in a set. If you tap one glass after another you will find that they do not all ring the same musical note, but some will probably sound a semitone higher than others, and a semitone corresponds to a difference in frequency of about 6 per cent. But if you make hydrogen atoms emit light, for instance, by passing an electric current through a glass tube which contains hydrogen, you find that the frequency of the light emitted by different atoms agrees to better than one part in ten thousand! So hydrogen atoms are not a motley lot. On the contrary, they are very much alike.

Now that we have seen the difficulties—and they seem quite formidable—let us see if they can be overcome. We shall start with the first difficulty. Is it true that a circling electron is bound to emit electromagnetic waves? The electromagnetic theory says, yes; but quantum theory says, no! According to quantum theory, electromagnetic waves (such as light waves) cannot be produced in arbitrarily small amounts. If an electron spirals toward the nucleus, in the way required by electromagnetic theory, it emits light all the time, and the amount emitted during one turn is much smaller than the minimum “export” permitted by quantum theory. Thus the electron cannot emit light continually, and hence it will not spiral toward the nucleus!

Our first difficulty seems to have been overcome, but we have run into new trouble. By the argument just expounded, an electron can never emit light at all. Electromagnetic theory demands that an electron must spiral (or in other ways lose speed gradually) in order to emit light. Quantum theory forbids the electron to emit light in a gradual fashion. How then does light ever come to be emitted?

The Danish physicist, Niels Bohr, was with Rutherford

when the latter first conceived the idea of the atomic nucleus. Bohr tried to elaborate the idea that the electrons circle around the nucleus like little planets, and promptly ran into the difficulties just described. However, they did not deter him. He was convinced that the idea was basically sound, and that there must be some way of reconciling the conflicting demands of electromagnetic theory and quantum theory. He had a very valuable guide in the frequencies of light emitted from hydrogen atoms. The spectral lines of hydrogen had been measured long ago (see Plate 3) and it had been found that their frequencies represented a regular sequence, governed by a simple mathematical formula; but no explanation for this regularity had been found.

Bohr's way of reconciling electromagnetic theory and quantum theory was as follows. Since quantum theory definitely stated that light could not be emitted in a continuous fashion, Bohr assumed that the electrons do not spiral inward but run in circles like planets. However, in order to make the emission of light possible, he assumed that an electron may, after running in a certain circle for some time, suddenly jump onto a smaller circle, at the same time emitting a light quantum (a photon). So far, quantum theory seems to be getting the better part of the deal; indeed electromagnetic theory has been completely ignored. However, everybody knows that electromagnetic theory is firmly founded on numerous accurate experiments with electrically charged bodies, electric currents, magnets, etc., and no physicist in his senses would propose a theory which was in contradiction with this powerful body of experimental facts.

Now the salient point is that Bohr's assumptions were not in contradiction with electromagnetic experience. All those facts which support electromagnetic theory were

gained through experiments with comparatively large bodies; the jumps which Bohr postulated would be far too small to be noticed there. For instance, an electron starting out on a circle with a diameter of two inches will, according to Bohr, approach the nucleus in a series of small jumps, with accurately circular portions in between; according to electromagnetic theory it should move toward the nucleus in a spiral. But if the jumps are very small it is very difficult

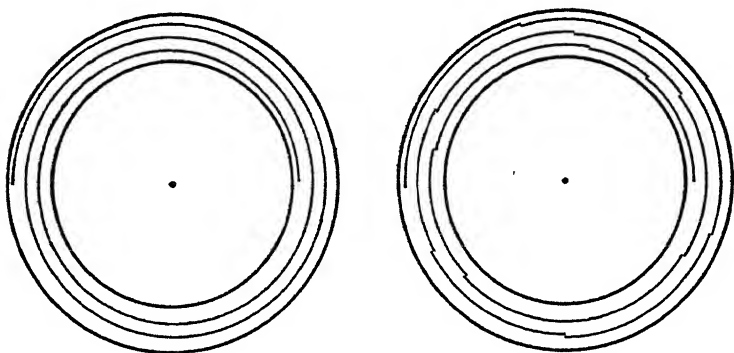


FIG. 20. Left: A spiral. Right: A succession of circular arcs with step-wise decreasing radius. Illustrates the difference between the motion of an electron in the field of a nucleus according to classical electromagnetic theory on the one hand, and by Bohr's theory on the other.

to distinguish the real path from a smooth spiral. In Fig. 20 you see a genuine spiral on the left, and on the right a curve made up of circular arcs with jumps in between. If you don't look very close you will hardly notice the difference. Actually, for an electron moving in an orbit of about two inches diameter the steps between successive circles would be very much finer than I have drawn them.

So Bohr proceeded to set up rules governing the diameters of the circles on which electrons were allowed to run.

He could not do this in an arbitrary fashion; his rules had to hold for big as well as for small circles, and in the case of big circles they had to be such that no contradiction with the laws of electrodynamics would arise. The rules had to be simple, for it is one of the strongest beliefs of physicists (and one which so far has always been vindicated) that the fundamental laws of nature are simple.¹ Finally they had to explain the spectral lines of hydrogen, the frequencies of the various kinds of light which hydrogen atoms are capable of emitting. From such considerations Bohr constructed his famous "model" of the hydrogen atom.

In this model, the smallest circle in which the electron can move has a diameter of 1.04×10^{-8} cm (four billionths of an inch). The other circles² have diameters which are 4, 9, 16, 25, etc. times bigger than the smallest circle, where these numbers are the squares of the natural numbers 1, 2, 3, that is, $4 = 2 \times 2$, $9 = 3 \times 3$, etc. The 20,000th circle would have a diameter of about an inch and a half, just about the size of Fig. 20. But if you work out the difference in diameter between it and the 19,999th circle, you would find that this difference is less than one-6000th of an inch, very much less than the steps indicated in Fig. 20. It would obviously be very difficult to detect any effects due to this small difference.

The law which governs the diameters of the allowed orbits is quite simple, as you have seen. It is so constructed

¹ Just what is meant by "simple" is not always easy to say. The equations of Einstein's Theory of Relativity would not look particularly simple to you, but a mathematician would assure you that they are fundamentally simple. Some people think that simplicity must be defined in esthetic terms: an equation is simple if it looks beautiful to a mathematician.

² Bohr also admitted certain elliptic paths; I am leaving those out to simplify matters.

that in the case of large orbits you can calculate the emission of light either from electromagnetic theory or from quantum theory and get the same result both ways, so that in the region where electromagnetic theory is well established there is no contradiction between it and quantum theory. And, finally, this model accounted accurately for the sequence of spectral lines of hydrogen which had been known for a long time and for which nobody could give an explanation.

You may ask, why do I keep calling it a "model"? Doesn't the hydrogen atom really look like this? Well, if we try actually to look at a hydrogen atom we run into a very peculiar difficulty. If we want to look at something we need some light. But if a light quantum impinges on an atom it will either go right through (in which case it does not help us) or it will disturb the path of the electron which we want to see. We are in the same predicament as a blind man trying to feel the shape of a soap bubble with his fingers; it bursts as soon as he touches it. His fingers are too clumsy for the exploration of soap bubbles; and for the exploration of the path of an electron in an atom, even the "fingers of light" are too clumsy.

I shall elaborate on this a little in the next chapter; but before that I shall try to answer a question which may well have been on your mind: What forces the electrons to run in certain orbits only? How does an electron know which orbits are "permitted"?

XVI

MATTER AND WAVES

LET US go back to the laboratory for a moment; I want to show you an experiment. Here is an evacuated glass tube built very much like a television tube; it contains an electron gun which sends a fine beam of electrons against a luminescent screen, and you can see the brilliant green spot where the electrons strike. Built in there is a little lever, pivoted in the middle like a tiny balance. To one end, a thin foil of mica is attached, poised above the beam, like a hatchet over a rope; a small piece of iron on the other end acts as a counterweight. Now I shall bring a magnet close to the tube, lifting up the piece of iron and thereby lowering the mica so that it intercepts the beam. What is going to happen?

First, the luminous spot on the screen moves a little as I bring the magnet nearer, because the magnetic field deflects the electrons slightly. But now the mica has moved into the path of the beam; the luminous spot becomes somewhat dimmer, and at the same time a whole host of new spots appears, making a neat sort of beehive pattern around the original spot!

The natural explanation would be to assume that our beam consists of waves, like a beam of light or a beam of X-rays. Actually, the pattern looks very similar to what one gets if a narrow beam of X-rays is made to pass through a sheet of mica and then allowed to fall on a photographic

plate. But our beam consists of electrons and not of waves! Or does it?

The French physicist Louis de Broglie (rhymes with Troy) predicted—over two years before such an experiment was carried out—that a beam of electrons would show wave properties. In light we have already met something which under certain circumstances behaves like a wave and in others like a stream of particles. De Broglie suspected that this kind of behavior was not limited to light, and that any stream of particles might, under appropriate experimental conditions, show the behavior of a wave. He did not know whether this actually was so, but he could reckon what wave length these waves would have if they actually existed. He showed that the wave length associated with a stream of particles can be obtained by this simple rule: Multiply the speed of the particles by the mass of an individual particle, and divide Planck's constant by the product.

It is easy to put this rule to the test. We know the mass of our electrons, and from the voltage by which they are accelerated in our tube we can figure their speed. We form the product of mass and speed, and divide Planck's constant by this product; this gives us the "calculated wave length." On the other hand, we can measure up the pattern on the screen, and we can look up some textbook on spacing of atoms in a mica sheet (the spacing of atoms in almost any imaginable material has been measured with the help of X-rays, as described in Chapter VI); from these data we can figure out what we may call the "measured wave length" (even though this procedure, too, involves some reckonings). If we do all this with great care we find excellent agreement between the "calculated" and the "measured" wave length. I don't want to bother you with the calculations, but I can show you one very simple (though only

partial) test of De Broglie's formula. If I lower the voltage through which the electrons in the tube are being accelerated to one-fourth, the speed of the electrons drops one-half, and according to De Broglie's theory the wave length must grow by the factor two. Actually you can see how the pattern on the screen expands while I lower the voltage, and when I have lowered it to one-fourth of the original value the dots on the screen will be just twice as far apart as in the beginning, which shows that the wave length has indeed been doubled.

I need not say that the experiment with mica foil is only one of many which were performed to test De Broglie's ingenious hunch. There can now no longer be any doubt that De Broglie was right and that a stream of electrons in some ways behaves like a wave.¹

You will probably ask, what sort of a wave? It is obviously not an electromagnetic wave, for a beam of electrons behaves in many ways quite differently from a beam of X-rays, even if both should happen to have the same wave length. To mention only one point of difference, a beam of electrons is deflected on passing through an electric or magnetic field while a beam of X-rays goes straight through. In light, or any other electromagnetic wave, the electric and magnetic fields vary in a periodic fashion with time, and the variation spreads through space with the speed of light. What is it that varies in the waves associated with a beam of electrons?

Curiously enough, the physicists have given it no name. The reason is that the quantity which varies here and which

¹ De Broglie's theory is not confined to electrons; even a stream of hydrogen molecules (each of which consists of two electrons and two hydrogen nuclei) behaves like a wave, the wave length of which can be calculated from the speed and the mass of the complete molecules, by De Broglie's formula. But this aspect of his theory is not going to concern us here.

I shall call the "wave field," for lack of a better name, is not accessible to direct measurement, in contrast to the electromagnetic field. Photons are "cooperative"; if you operate a radio transmitter, it sends out an enormous number of photons (if you want to look at it from the quantum point of view). All of them cooperate, adding up their tiny contributions to form a powerful wave which can be observed with comparatively coarse instruments enabling us to measure the electric and magnetic fields and follow their ups and downs. In any such measurement millions of photons are absorbed or deflected by the measuring instrument, but this does not disturb the wave much since it is made up of the contributions of many billions of photons. Electrons, however, are not cooperative in this sense; each electron wants a wave of its own. Hence in a beam of electrons we do not really have a single oscillation as in the waves emitted by a radio transmitter, but a multitude of waves, one for each electron, all very nearly—though not entirely—alike in wave length and direction. There is no possibility here of making millions of electrons cooperate to form a wave powerful enough to enable us to measure the "wave field." You may ask, could one not develop instruments delicate enough to study the "wave field" of a single electron? I don't say one couldn't, but it would do us no good, for any single measurement would affect the electron whose "wave field" we are trying to measure, and therefore the next measurement would refer to an entirely different "wave field." So we would again be in the position of the blind man trying to feel the shape of a soap bubble.

I am afraid all this sounds very vague and unsatisfactory, but I hope I have at least made the difficulty of the problem clear. The "wave field" associated with an electron is of an entirely different nature from the electromagnetic field asso-

ciated with a photon. The latter can be measured, if one makes use of the cooperation of many photons to produce a strong electromagnetic field; but electrons cannot be made to cooperate in producing a strong "wave field."

Let us now return to the question which we posed at the end of the last chapter: What forces the electrons to run in certain orbits only? I shall try to show you that De Broglie's theory provides a satisfactory answer to this question.

I shall frame this answer in two ways. The first, a rather crude one, runs as follows: If an electron runs in a circle, its associated wave must also be circular, closed in itself. We shall again make use of the trick of representing the wave by a wavy line, remembering that this is merely graphical representation of a quantity (the "wave field") which at any one instant varies from one point to another in the way indicated by the line. If we do this, a wave which is closed in itself must be represented by a "wavy circle," a circle with waves superimposed. Figure 21 shows several of those "wavy circles," and one thing is immediately obvious: such a circle can have three or four or five waves, but not three and a half waves. Now if we want an electron to run, for instance, on a circle such that the associated "wave field" has three waves in the circle, we must choose the diameter of the circle so that its circumference

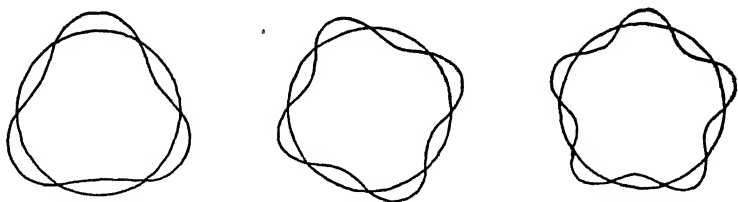


FIG 21. Circular wave patterns, containing 3, 4, and 5 complete waves.

is exactly three times the wave length. The wave length depends on the speed of the electron, and the speed in turn is determined by the diameter of the circle on which we want the electron to run. By trial and error (or by some rather simple mathematics) one can find the circle for which these things just fit together. If we try to make the electron run on a slightly bigger circle, we find that the speed of the electron has decreased and its wave length therefore increased, but not enough for three waves to cover the bigger circle; if we go on increasing the circle we eventually come to a point where a "wave field" with four waves will just fill the circle, and so on.

Now the nice thing is that if you work out the diameters of these circles from De Broglie's formula, in the way just explained, you get exactly the circles which Bohr postulated in his "model" of the hydrogen atom. These orbits are "permitted" because the "wave field" can be arranged so that it corresponds to the motion of an electron in one of these orbits. Motion in other orbits is not "forbidden" but just unthinkable, since there is no arrangement of the "wave field" to correspond to such a motion.

From this point of view the arrangement of the "wave field," or, as it is commonly called, the "wave function," seems to be the thing of primary importance; the electron would appear to be in some way the slave of its own wave function. The mathematical development of this point of view leads to what is called "Wave Mechanics." Wave mechanics is essentially a refinement and a generalization of our argument of the "wavy circles." The procedure is roughly as follows. First, an equation is set up, the solution of which is an ordinary straight wave; this can be done in close analogy to the theory of sound or light, and is essentially what De Broglie did. Next, the equation has to be

modified so that it corresponds no longer to an electron moving freely but to one affected by the attractive force of the nucleus. Finally one has to find a solution of this modified equation. This is not quite what we did earlier; before we worked out how the electron would move if there were no waves, and then bent the wave around to fit the path of the electron; now the electron is used only to set up the wave equation and then disregarded.

If you proceed in this way the "forbidden" orbits never enter the picture at all. The wave equation can be solved mathematically and is found to have a number of solutions, the wave functions, each corresponding to a certain energy of the electron. We no longer speak of an electron jumping from one orbit to another, but of the transition from one wave function to another; you can imagine one wave pattern fading out while a different pattern takes its place.

That a wave equation should have a number of separate solutions sounds like a highly abstract and mathematical statement, but actually it merely states a fact with which every player of a wind instrument is familiar. A trombone player can make his instrument sound a number of different musical notes ("harmonics" or "partials") merely by altering his lip pressure and way of blowing. These notes are solutions of the wave equation which is determined both by the length of the tube and the properties of the air inside it. If the instrument warms up the properties of the air change and the pitch goes up as a result; and the player can also change the pitch by shortening or lengthening his instrument. But as long as the wave equation is not changed the player is limited to a number of separate notes and is quite unable to play any note in between. The bugle player cannot change the length of his instrument and is

confined to those few solutions of his wave equation of which all military signals are made up.

This wave-mechanical picture of wave patterns is much harder to visualize than the concept of electrons running in circles, but it is very amenable to mathematical treatment. Methods for solving wave equations were already highly developed, in the theory of sound and of light, when the Austrian physicist, Erwin Schroedinger, showed how De Broglie's equation had to be modified to take account of the attraction between the electron and the nucleus. The Schroedinger equation, as it is commonly called, may still be said to be the basis of the whole theory of electrons in atoms, although important refinements were introduced later, notably by the English physicist, P. A. M. Dirac.

Almost simultaneously with Schroedinger's theory, an entirely different theory was proposed by the German physicist, Werner Heisenberg. He did not use waves at all; instead, he altered the mechanical laws which govern the motion of electrons. His theory is even more abstract and mathematical than Schroedinger's; its most astounding feature is the use of a generalized kind of mathematics in which the product of two quantities may depend on the order in which they are multiplied, that is, in which A times B is not necessarily the same as B times A .¹ There followed a short time in which physicists excitedly took sides for one or the other theory; and then it was found that whenever

¹ Such a type of mathematics is neither mystical nor crazy. If A and B are ordinary numbers then A times B means "take A as many times as B indicates, and add up," and in this case A times B is the same as B times A . But mathematics thrives on generalizations, and A and B may be symbols which do not represent ordinary numbers, and in this case the idea of multiplication, too, becomes generalized and no longer means repeated addition. Mathematicians have long been familiar with non-commutative multiplication.

the two theories were applied to the same problem they gave exactly the same result, which seemed very astonishing since the two theories looked so entirely different. Finally it was found that, from a mathematical point of view, the two theories were identical despite the entirely different way in which they were formulated.

This mathematical identity of two theories, one based on the concept of particles, the other on the concept of waves, corresponds, on the mathematical plane, to the idea of complementarity which I outlined roughly on page 111. We can now say that not only light but material bodies also can be described in terms of either particles or waves. Which of the two descriptions is the more appropriate depends on the kind of information we want. If we want to locate an electron in an atom we can do so (in principle), but the most careful possible way of doing it, namely, by "just looking," cannot avoid disturbing the electron by the light quanta used to illuminate it. As a result, the wave function becomes indefinite. On the other hand, if we are interested in the energy possessed by the electron in one of its stationary states, the wave equation and its possible solutions are the things that matter, and the localization of the electron becomes indefinite.

It is perhaps a little easier to grasp these things if we consider a free electron, rather than an electron tied to a nucleus. If we want to see where the electron is we have to illuminate it, and at least one light quantum has to bounce off the electron if we want to see it.¹ As a result of

¹ The human eye is not quite sensitive enough to detect a single light quantum; about 50 light quanta are needed to give the impression of a flash of light. Yet the experiment I am describing, while fictitious, is not essentially impossible; for instance, there are photoelectric cells which can detect single light quanta.

this collision, the speed of the electron is altered by an indefinite amount, and Heisenberg showed that the more accurately we try to locate the electron, the more its speed is likely to be changed. Heisenberg also discussed the possibility of experiments for measuring the speed rather than the location of the electron and showed that here again the light quanta which we have to use disturb the electrons. As a result, the more accurately we measure the speed of the electron, the more we lose any knowledge of its previous location we may have possessed. So it does not help much to determine first the location and then the speed of the electron, or vice versa, because the second experiment always partly invalidates the information obtained from the first experiment. The quantitative formulation of this state of affairs is the famous "uncertainty relation" of Heisenberg, which may be stated as follows: If one attempts simultaneously to determine the location and the speed of a particle, both results are bound to be somewhat uncertain, and the product of the two uncertainties can never be smaller than a definite limit, which is found by dividing Planck's constant by the mass of the particle.¹ We can choose our experimental arrangement so as to increase, for instance, the accuracy of speed measurement; but then the location of the electron becomes at once less accurately known. In the limit, we may imagine that we have measured the speed of the electron (and thereby the wave length of its wave) with complete precision; then its wave function is perfectly determined, but the location of the electron is completely uncertain: we have lost the electron. On the other hand, if we succeed in localizing the electron with perfect accuracy, its speed (and thereby its wave

¹ The product of the two uncertainties can of course be greater than this limit, if the experiment is done in an unskillful manner.

length) becomes completely uncertain, and its wave function becomes meaningless.

Once the fundamental identity of the theories of Heisenberg and Schroedinger had been recognized, theoretical physicists could make use of the best features of both, and rapid progress was made in the understanding of the arrangement of the electrons around all kind of nuclei. The mutual repulsion between the negatively charged electrons and the fact that each electron must have a wave of its own created very difficult mathematical problems, but they were overcome in all but the most complicated cases. The arrangement of the spectral lines, not only of hydrogen but of practically all elements, was analyzed and comprehended to a very great extent. To describe all this work with any reasonable degree of completeness would require another book like this one.¹ I shall only mention two facts which are related to things I mentioned before.

Each electron wants its own wave function; when there are several electrons in an atom this leads to an arrangement of electrons which is usually described—rather crudely—as a sequence of concentric shells around the nucleus. On the innermost shell there is room for two electrons; the next two shells have room for eight electrons each, the next two for 18 electrons each, the next two for 32 electrons each; but before these are full we run out of elements. Those atoms where all the electrons are arranged in complete shells are very hard to “deprive of even one electron, and have no tendency to acquire additional electrons; as a result, they do not form any chemical compounds. They are the noble

¹ Two Danish friends of mine, Drs. C. Moller and E. Rasmussen, have written such a book, and it has been translated into English, under the title “The Atom and You.” It is at present sold out, but watch for a new edition, if you wish to know more about atoms.

gases helium, neon, argon, krypton and xenon¹ mentioned on page 118; the fact that they are all gases is further evidence of the unsociable character of their atoms. Elements immediately following one of the noble gases have atoms in which the outermost shell contains just one electron; this electron, all alone on its shell, is rather loosely bound and therefore easily removable. These are the alkali elements lithium, sodium, potassium, rubidium, and cesium. Their atoms easily lose one electron and become singly charged positive ions. This fact explains to a great extent their chemical properties, and also some of their physical properties. Cesium, for instance, is used for photoelectric cells (see page 106) because its outermost electron comes off with particular ease. On the other hand, the elements just before the noble gases lack just one electron in each atom to make a complete shell; they are the so-called halogens: fluorine, chlorine, bromine and iodine.² Their atoms have a strong tendency to take an electron away from some other, less acquisitive, atoms and to form singly charged negative ions (see page 70); this accounts largely for their characteristic chemical properties. In this way the chemical and, to some extent, the physical properties of all elements can be correlated with the arrangement of the electrons in their atoms and, especially, their arrangement in successive shells.

This shell structure explains a fact long known to chem-

¹ Their atomic numbers (their nuclear charges, measured in units of the charge of a hydrogen nucleus) are 2, 10, 18, 36, and 54, as it follows from the shell scheme. The next in this series (and the last) is element 86; its three known isotopes are all radioactive and have separate names: radon, thoron, and actinon. As a common name, the word "emanation" is often used.

² Atomic numbers 9, 17, 35, and 53. Strictly speaking, one ought to include hydrogen (which stands before helium), but hydrogen is in a class by itself.

ists, namely, that if the elements are arranged in order of increasing atomic weight, similar chemical properties repeat themselves in a fairly regular pattern (the so-called periodic system of elements). It also explains the fact—which had puzzled the chemists—that there were a few apparent exceptions from the regular arrangement of the elements. For instance, argon (atomic weight 39.9) had to be placed before potassium (atomic weight 39.1) so as not to disturb the pattern of the “periodic system.” Now we know that the correct arrangement of the elements is not by their atomic weights but by nuclear charge, that the correct “atomic number” of an element is its nuclear charge, measured in units of the charge of the hydrogen nucleus.

Previously we defined an element as a substance in which all atoms had their electrons arranged in the same way. Wave mechanics teaches us, however, that not only the number but the arrangement also of the electrons in the atom is determined by the charge of the nucleus. So we can change our definition of an element and say: an element is a substance in which all the atomic nuclei have the same electric charge. This definition goes literally to the core of the matter. Imagine a nucleus stripped of all its electrons; the fact that it has a certain electric charge enables it (if you provide a sufficiency of electrons) to refurnish itself with a complete suit of electrons with all the shells and frills which go to make a correctly dressed atom. By dehydrating food, a lot of shipping space can be saved. Just imagine we could “de-electronate” atoms! The entire annual steel production of the United States could be shipped in a single beer bottle full of iron nuclei. Unfortunately, all the power production of the world would be entirely insufficient to do the “de-electronating.” If by

some miracle we could acquire a bottle full of iron nuclei, their mutual electric repulsion would cause an explosion which would make the atomic bomb look like a firecracker.

You may say that defining an element through the electric charge of its nuclei is impractical because it is difficult to measure this charge. This is not quite true. Actually, there is a method of chemical analysis being used more and more in industrial routine which actually measures the nuclear charge. If you want to know what alloy the enemy uses for his anti-tank shells, you take a shell fragment, put it into an X-ray tube and bombard it with fast electrons. As explained earlier, all elements under these conditions emit so-called characteristic X-rays, the wave length of which decreases in a regular way as you go from one element to the next. Quantum theory gives a simple explanation for these characteristic X-rays. They are caused by the two electrons in the innermost shell. If you bombard your material with fast electrons it occasionally happens that one of these two innermost electrons gets knocked out of the atom, thus creating a vacancy. This vacancy is soon filled by some other electron falling into it (usually from the next shell) and the excess energy is sent out as an X-ray quantum. If you go to an element with higher nuclear charge, the innermost electrons are more strongly attracted, more energy is liberated in filling the vacancy, therefore the X-ray quantum gets more energy and the wave length of the X-rays must get shorter. With the help of quantum theory one can actually calculate the charge of the nucleus from the wave length of the characteristic X-rays. So if your assistant, after taking an X-ray spectrum of the shell fragment and comparing the strength of the different lines, reports that the sample contains so and so much per cent of iron, cobalt, and molybdenum, he

has really measured the nuclear charge of a large number of atoms, picked at random (the fast electrons in the tube do the picking) and found that so and so many per cent of them have nuclear charges of 26, 27, and 42 times the charge of a hydrogen nucleus.

Let me review briefly the contents of this chapter. The arrangement as well as the number of electrons in an atom is entirely determined by the electric charge of the nucleus. It can be described either in terms of particles or in terms of waves, and the two descriptions have their counterparts in the mathematical theories of Heisenberg and Schrodinger. The particle aspect and the wave aspect are complementary; any experiment designed to study one aspect automatically pushes the other aspect into the background. In the case of a free electron, this complementarity is expressed through Heisenberg's "uncertainty relation." Each electron has a wave function of its own, and this results, in the case of atoms with several or many electrons, in a structure which can be crudely described as a shell structure. With this shell structure, many of the chemical and physical properties of the elements can be correlated.

XVII

THE ATOMIC NUCLEUS

WE ARE NOW entering a new field of atomic physics—a field called nuclear physics because it deals with the properties of the atomic nucleus. So far we have encountered two of its properties: the mass and the electric charge. The electric charge is always positive; it is a whole multiple of the charge of the hydrogen nucleus, and its value decides what kind of element the nucleus belongs to. If the charge is fixed a nucleus may in some cases still have different values of the mass; such nuclei are said to belong to different isotopes of the same element. Isotopes of one element are almost identical in their chemical and most of their physical properties and therefore very hard to separate. The atomic weight as determined by chemical methods is really the average weight of the several isotopic nuclei¹ of which a given element is a mixture. Whenever necessary, I shall use the phrase “isotopic weight” to distinguish the weight of the nuclei of a particular isotope from the average of the isotopes of an element. It is common to denote an isotope by the name of the element with

¹ If you weigh yourself on a public weighing machine you determine the weight of your body plus the weight of your clothes. Similarly, nuclei are usually weighed with their electrons on. It would be easy to subtract the weight of the electrons, but it is not commonly done. In what follows, whether I say “the weight of the atom” or “the weight of the nucleus,” I always mean the weight of the complete atom, that is, of the nucleus fully dressed.

the weight of the isotope written after it; for instance, the two isotopes of lithium are written lithium 6 and lithium 7.

From the few isotopic weights mentioned so far it may have struck you that they all seem to be whole numbers (integers). Since the weight of the hydrogen atom is the unit in which all atomic and isotopic weights are measured the idea suggests itself that nuclei are built up from hydrogen nuclei. If that is so, then the hydrogen nucleus assumes a much greater importance than hitherto; it is not just the nucleus of one element, hydrogen, but a building-brick of all nuclei, ubiquitous like the electron. In a sense it is even more important than the electron because the nuclei contain practically all the weight of matter and also determine its chemical properties. A particle of such importance deserves a name of suitable dignity, and we shall from now on call the hydrogen nucleus by its more solemn name, "the proton," which means (in Greek), the first one.

However, nuclei cannot be built up entirely of protons, or else the atomic weight, that is, the weight of the nucleus divided by the weight of the proton, would always be the same as the atomic number, which is the charge of the nucleus divided by the charge of the proton. For instance, the helium nucleus has twice the electric charge of a proton, but its weight is four times greater, so it seems to contain some "ballast" without electric charge but weighing as much as two protons. And the same is true for all other nuclei; the atomic weight is always greater than the atomic number (except, of course, in the case of hydrogen itself) and so all nuclei must contain some of this ballast.

For this reason it was soon suggested (independently by a number of people) that there may exist a kind of proton without an electric charge, a "neutron" as it was called because of its electrically neutral character. If one accepts

this suggestion a helium nucleus, for instance, would consist of two protons (which would account for its known electric charge) and two neutrons (which would bring up the atomic weight to its known value 4). For some years the neutron remained a purely hypothetical particle, which accounted for the extra weight of atomic nuclei, but which was not supported by any direct evidence; there were other, more plausible, ways of explaining the extra weight.¹ So it clarified and simplified matters enormously when Chadwick discovered (in 1930) that particles with no electric charge and the same weight as a proton could actually be knocked out of atomic nuclei. After this discovery one could discard all other alternatives and definitely regard all nuclei as being built up from protons and neutrons, and this view has since been confirmed by a very large number of experiments.

Most of the experiments from which we have learned something about the structure of atomic nuclei are of the kind commonly called "atom-smashing." In these experiments the structure of nuclei is actually changed. Sometimes a nucleus is broken down into two or more smaller nuclei, and then the term "smashing" may be considered appropriate (although its suggestion of brutality does not appeal to me); sometimes the resulting nucleus is bigger than the original one and the process had better be called

¹ One could, for instance, construct a nucleus by first building up its entire weight out of protons, and then reducing the excess electric charge so produced by inserting electrons. For instance, a helium nucleus might be built up from four protons and two electrons; the negative charge of the electrons would bring the charge down to the required value 2. Quantum mechanics squirmed at the idea; an electron, localized as accurately as the minute size of the nucleus would demand, would have a tremendous range of velocities, according to Heisenberg's uncertainty relation, and tremendous force would be required to hold it. Yet many physicists favored this view since it used only particles actually known to them.

"atom-building." Physicists among themselves speak of "nuclear transformations" or, if the nucleus is broken down into smaller nuclei, of "nuclear disintegrations."

We have already met one type of nuclear disintegration, the disintegration of a polonium nucleus into a helium nucleus (called an alpha particle as long as it is in rapid flight) and a nucleus of a certain isotope of lead. This disintegration is spontaneous: it happens all by itself without any help from the physicist. Moreover, the polonium nucleus proudly refuses any help; extreme heat and cold, strong electric and magnetic fields, all sorts of powerful chemical reagents have been tried and have been found utterly ineffective in changing the rate at which the polonium nuclei disintegrate. This is not surprising in the light of our present knowledge since each nucleus is protected by its several layers of electrons as by an elaborate system of springs which prevent any serious shock from reaching the nucleus. And if two nuclei should, by any chance, come close together their electric repulsion would drive them apart again long before they could actually come into contact.

The question then naturally arises, what makes the polonium nucleus disintegrate? This is a very interesting question, and its answer cannot be obtained without the help of quantum theory. But before we can discuss this problem I must tell you a little more about atomic nuclei in general.

I told you on page 127 that if one sends alpha particles through a thin metal foil, most of them go straight through, but a few suffer a slight deflection. Those which are deflected are those which happen to pass close enough to a nucleus to be appreciably affected by its electric field. Those which pass closer to a nucleus get more strongly deflected, but near misses are rarer than wide misses, and

therefore large deflections are rarer than small ones. Yet occasionally an alpha particle will make straight for a nucleus, and then everything depends on how much electric charge the nucleus has. If its electric charge is big enough the alpha particle will be turned back before it touches the nucleus; otherwise the alpha particle will score a hit, and then interesting things may happen.

Rutherford was the first to succeed (in 1917) in observing a nuclear transformation caused by an alpha particle hitting a nucleus. The apparatus he used was very simple (Fig. 22). First, he observed the numerous light flashes caused by the alpha particles from a suitable radioactive element on falling on a zinc sulphide screen; both the alpha

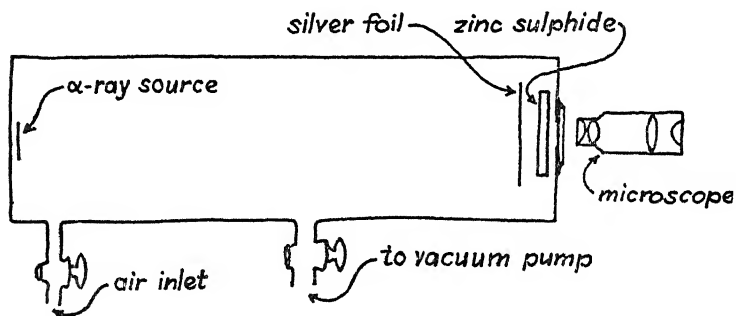


FIG. 22. Schematic diagram of the apparatus with which Rutherford discovered the artificial disintegration of atomic nuclei.

ray source and the screen were inside an evacuated container. Next, he placed a thin foil of silver over the screen, just a little thicker than necessary in order to prevent the alpha particles from reaching the screen, and convinced himself that there were indeed no more light flashes to be seen. Then he opened a stopcock which permitted some air to enter the container. This should have acted as an additional obstacle to the alpha particles and might have re-

duced the number of light flashes further if it had not already been zero. But actually the air had the opposite effect: light flashes appeared again on the screen, very few indeed, but enough so that one could be sure they were real. Now air is a mixture of one part of oxygen with four parts of nitrogen; which of the two was causing the flashes? This can easily be tested. We pump the air out again and fill the container with oxygen (for instance, from a commercial oxygen cylinder). No flashes. If, on the other hand, we fill the container with pure nitrogen instead of air, the flashes are back again, and even more numerous than before. This shows that the flashes are due to the presence of the nitrogen. If we take the alpha ray source away the flashes disappear. The same thing happens if we move the silver foil back from the screen and close to the source, so that the alpha particles are stopped before they have a chance of hitting a nitrogen nucleus. This shows that the flashes depend on the action of alpha particles on nitrogen.

But what actually causes the flashes? It must be something more penetrating than the alpha rays, or else it could not go through the silver foil. By various experiments, including measurements of the electric and magnetic deflection of these penetrating particles, Rutherford showed they were protons. If he filled his container with hydrogen instead of nitrogen, he also observed flashes caused by protons. This was of course expected, since alpha particles traveling through hydrogen were bound occasionally to collide with a hydrogen nucleus, alias proton. In such a collision the light proton would be sent flying like a golf ball hit by a driving iron. But the protons obtained in this fashion are not as penetrating, and hence not as fast, as those which could be obtained from nitrogen. This is im-

portant for two reasons. It shows that the protons which one gets with nitrogen really come from the nitrogen and not from some hydrogen which somehow found its way into the container (for instance, in the form of moisture; you remember, water contains hydrogen). Furthermore, it shows that what the alpha particle does is not merely to knock one of the protons out of the nitrogen nucleus while the other protons and neutrons watch with bored faces. On the contrary, they even give the departing proton an extra kick to speed it on its way. This is surely a rude way of treating a fellow-proton with whom one has lived for millions of years!

On one important question the experiment gives no information. What happens to the alpha particle? Does it bounce off or does it stick? Rutherford's apparatus is no good for answering this question. Even if the alpha particle did bounce off it would be very hard to identify it among the millions of alpha particles from the source. It has not more penetrating power than they, more likely less, having lost speed in the collision.

Here C. T. R. Wilson's wonderful invention, the cloud chamber, proves its value. Plate 5 shows a number of alpha particles running through nitrogen, and one of them colliding with a nitrogen nucleus. From the point of collision a track, somewhat thinner than that of the alpha particles, indicates the path taken by the proton; being faster and lighter, the proton does not leave as dense a trail of destruction as the alpha particle and hence its track is thinner. A second track, short and thick, points to the other side; it has just the right length and direction to be ascribed to the remainder of the nucleus, with the alpha particle stuck on. If the alpha particle had bounced we should see a third track leading away from the point of

collision. The picture you see is one of several thousand, each with several dozen alpha particles on it; of all those many thousand alpha particles, only a few had a collision in which a proton was ejected. Whenever that happened there was no third track to indicate that the alpha particle had bounced off. So this is the answer of the cloud chamber: If an alpha particle knocks a proton out of a nitrogen nucleus it gets itself stuck to the remaining nucleus.

The fact that the alpha particle unites with the nitrogen nucleus which it hits accounts for the rude way in which the proton is thrown out by its own family. The arrival of the alpha particle causes great excitement among the protons and neutrons of the nitrogen nucleus who suddenly find their company augmented by four new members (you remember, the alpha particle is a helium nucleus and consists of two protons and two neutrons); in the excitement one proton falls overboard and is blown away by the electric repulsion of the other protons. Or, to put it a little more scientifically, the entry of the alpha particle into the nitrogen nucleus liberates a considerable amount of energy, and sets all the protons and neutrons into vigorous and turbulent motion; this continues for a time¹ until by some chance irregularity one of the protons gets an extra high speed which enables it to tear itself away from the rest of the nucleus; its speed increases still further as it is driven away by the electric repulsion of the remaining nucleus.

You will probably ask, why doesn't it occasionally happen that a neutron "falls overboard" rather than a proton? The answer is it does happen, only it is much more difficult to observe. The neutron has no electric charge and therefore can slip through solid matter practically without resistance.

¹ There are indirect ways of estimating this time; it is much less than a trillionth of a second.

It does not act on the electrons and therefore it does not tear them off (ionize the atoms) as an alpha particle or proton does. It does not get deflected by the electric field of atomic nuclei. It leaves no trail of destruction and can therefore go right through a cloud chamber without leaving a track. Only when it happens to run smack into another nucleus does its presence become known. If it collides, for instance, with a hydrogen nucleus (a proton) it bounces off and the proton is sent flying. This proton then can produce a track in a cloud chamber, or it can cause a light flash on a zinc sulphide screen. So you see that in order to observe a neutron we must have two nuclear collisions: one between an alpha particle and a suitable nucleus, whereby a neutron is ejected, and then a collision between the neutron and, for instance, a proton, whereby the latter gets enough speed to become observable.

The discovery of the neutron was a dramatic story in which three nations participated, and with some amount of imagination one might even think that national characters were reflected in the way the scientists in question acted. The German, W. Bothe, noticed that beryllium,¹ when bombarded with alpha particles, gave off some kind of radiation which appeared to have unusual properties. He proceeded to study the phenomenon in a thorough and systematic fashion and it seems likely that he would have eventually proved the presence of neutrons. The French scientists, Irène Curie (daughter of the famous Madame Curie who discovered radium) and her husband, Frederic Joliot, observed that the mysterious radiation produced proton tracks in a cloud chamber containing hydrogen, and that these tracks did not start from the bombarded beryl-

¹ Element number 4; a hard silver-white metal. Used industrially for making non-magnetic watch springs, by alloying it with copper.

lium itself but at various places inside the chamber. This was a hot clue, but it was missed because Curie-Joliot had a preconceived idea about the nature of this radiation. The Englishman, James Chadwick, remembered that the idea of a "proton without charge" had been discussed before and that Rutherford had even made an unsuccessful attempt, some years earlier, to force protons and electrons to combine, and thus to produce neutrons, by passing a strong electric discharge through hydrogen. So Chadwick set out to measure the mass of those unknown particles which produced tracks starting right inside the cloud chamber.

This is a difficult job. It was clear that the particles were not electrically charged, or else they would have produced cloud-chamber tracks starting right from the source, the beryllium. As a result, they are not deflected by either electric or magnetic fields. However, Chadwick managed to get at least an approximate measurement of their weight in the following way. He first filled his cloud chamber with hydrogen and observed the length of the tracks which were produced by the protons set in motion by the impact of the unknown particles; then he repeated this experiment with a cloud chamber full of oxygen, when he again got tracks (shorter and thicker ones) caused by collisions of his particles with oxygen nuclei. From previous measurements it was known how to calculate the speed of hydrogen and oxygen nuclei from the length of the tracks they made in a cloud chamber. In this way it was found that the impact of the unknown particle gave about eight or nine times greater speed to a proton than to an oxygen nucleus.

From here on it is a simple problem in mechanics. The oxygen nucleus is sixteen times heavier than the proton. If the unknown particle were much heavier still it would give the same speed to the proton and to the oxygen nu-

cleus, on colliding with one of them (namely, twice its own speed). On the other hand, if it were very light, much lighter even than the proton, then one can calculate that the proton would receive 16 times as much speed as the oxygen nucleus. But if the unknown particle weighed the same as the proton, then the speed ratio between protons and oxygen nuclei ought to be 8.5, and that is just about what Chadwick found. He could thus report that the radiation emitted by beryllium under alpha-ray bombardment contained ¹ some particles which had about the same weight as protons but no electric charge, and for which the name "neutrons" seemed appropriate. This report made Chadwick the discoverer of the neutron.

This is about as far as the art of atom-smashing got, as long as people could only use natural alpha particles for bullets. They succeeded in causing nuclear transformations in most of the lighter elements, up to a nuclear charge of about 20, and much work was done in studying the number and speed of the protons and neutrons emitted. All these investigations were slow and laborious, largely because the supply of alpha particles is limited and only a few in a million happen to hit a nucleus. One very important discovery was made during this time, the discovery of artificial radioactivity, whereby Curie-Joliot made up for having missed the discovery of the neutron. I shall speak about this important subject later in the book. But on the whole it was the invention of atom-smashing machines (of which the cyclotron is the best-known) which started nuclear physics on its present tempestuous career, and I am now going to tell you about these machines.

¹ "Contained," not "consisted of." The bombarded beryllium also sends out gamma rays (very penetrating X-rays), just to make things more difficult.

XVIII

MACHINES FOR ATOM-SMASHING

AFTER ALL, what is an alpha particle? Nothing but a fast-moving helium nucleus, with a kinetic energy of some five or six million electron-volts. Now we have seen, in Chapter XIII, how easy it is to strip a helium atom of its two electrons and thus get a helium nucleus, also that an ion gun for accelerating these nuclei is quite a simple affair. So why don't we just make an ion gun in which helium nuclei get accelerated by a voltage of five or six million volts¹ and make our own alpha particles?

Let us try a little to visualize a million volts. A flashlight battery gives three volts, that is very little. The electric mains usually deliver 115 volts; if one touches both wires one gets an unpleasant shock, and occasionally people even get killed, but with a very moderate amount of insulation, 115 volts is quite safe. In television sets, voltages of several thousand volts are used. For such voltages, air is no longer a reliable insulator; if you bring two wires closer together than about an eighth of an inch you are apt to get a spark from one to the other. As the voltage is further increased the air gap which a spark can traverse gets rapidly greater. You may remember those electrostatic machines which are used in schools to demonstrate electric phenom-

¹ Actually, a helium nucleus, because of its double charge, gets twice as much kinetic energy as an electron if both are accelerated by the same potential. Hence we need only three million volts to give an energy of six million electron-volts to a helium nucleus.

ena. They have two discs of glass or ebonite (a foot or two in diameter) which can be turned with the help of a handle. As you turn them, electric charges are conveyed onto two metal balls and the potential difference between these two metal balls grows until, with a loud crack, a spark occurs between them, looking just like what it is, a tiny lightning stroke. Some of these machines can make about a hundred thousand volts and produce sparks several inches long.

A hundred thousand volts still is far less than we want. We might build an electrostatic machine some ten times bigger than the usual school model. That would be a monster with discs twenty feet in diameter, and if it really did produce a million volts (which I doubt) it would make sparks several feet long, each accompanied by a deafening crack. Actually, we do not want those sparks, since they make the voltage drop away down every time they happen; so we have to keep all the metal conductors several feet apart and away from the walls of the room. Also, all the conductors must be thick and well-rounded; wherever there is a sharp corner you get a hissing and crackling discharge of electricity, visible in the dark as a luminous brush or tassel, and this discharge represents a drain of power and hence lowers the voltage that can be achieved. To build a machine of that size would be quite a job, and a machine for three million volts would be again about three times larger and at least twenty-seven times more expensive. So you see, to make alpha particles artificially is not as simple as it sounds.

The ion gun also presents a problem. If you took a little ion gun such as we used in Chapter XIII, and put it on a million volts it would just disappear in a blue flash. An ion gun which can operate at a million volts can shake hands with a naval gun. It is many feet long, made of numerous

rings of strong metal and porcelain, specially designed to withstand the strong electric fields, and is evacuated by several large-size pumps.

However, all these difficulties can be overcome and machines have actually been built and operated in which ions can be accelerated by electric potentials up to about four million volts. These machines do not use rotating plates but an endless belt made of paper or woven material. This idea was first used by an American physicist and engineer, R. J. van de Graaff, and proved very successful. Many of these machines are now in operation in various laboratories and they are usually called Van de Graaff machines, or simply, Van de Graaffs.

The principle of a Van de Graaff is that of the belt conveyor (see Fig. 23). You keep shoveling sand onto the left end and the belt will carry it away and dump it onto the heap on the right. As the heap gets higher it becomes necessary to tilt the belt at a steeper and steeper angle; eventually the sand begins to slip back on the belt, and that limits the size of the sand-heap that you can make with a given conveyor. If you want to make a larger sand-heap you have to use a longer conveyor belt. It is important to support the belt in several places with rollers to prevent it from sagging; if it sags the sand will begin to slip back at a smaller tilt than with a belt which does not sag.

All these details of a conveyor belt have their counterparts in the Van de Graaff machine. At the end on the left, electric charges are sprayed onto the belt with the help of a row of needle-points which are connected to a supply of about 20,000 volts (built somewhat like the power pack of a television set). The charges are conveyed to the large metal sphere on the right where they are sucked off the belt by another row of needle-points. As a result more and

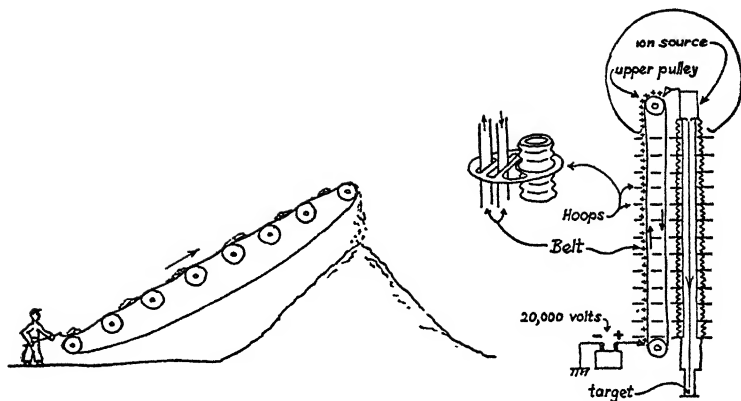


FIG. 23. The belt conveyor (left) illustrates the principle of the electrostatic belt generator (Van de Graaff) shown schematically on the right. A 20,000 volt auxiliary unit sprays positive charges onto the fast-moving belt which carries them to the large metal sphere on top. The charges return as a beam of fast ions down the ion gun (to the right of the belt). The insert shows two of the corrugated porcelain insulators of which the ion gun is built up, together with one of the hoops which protect the belt from non-uniform electric fields (see text).

more charge accumulates on the sphere, and its increasing electric potential corresponds to the increasing height of the sand-heap. Eventually the gradient of electric potential along the belt gets so large that the charges are beginning to "slip back"; sparks develop along the belt and the potential of the sphere increases no longer. If we use a longer belt, the potential on the sphere can be raised to a higher value before the sparking begins. For best operation it is important to make the potential gradient uniform all along the belt. This is done by using a large number of wire hoops, forming a kind of elongated cage all around the belt; these hoops are connected by electric resistors or similar devices which guarantee that the potential rises in equal steps from one hoop to the next. Without these hoops, the po-

tential will drop quite fast in the neighborhood of the sphere and much more slowly at greater distances; and sparks will develop near the sphere at a much lower potential than if the potential gradient is uniform. The hoops are therefore analogous to the rollers used in a belt conveyor to keep the belt from sagging.

The ion gun is built on a similar principle so as to maintain the potential gradient. It is made from alternate rings of steel and porcelain, about six inches in diameter. The porcelain rings are corrugated to make it more difficult for electric sparks to develop (the same trick is used in industrial high-voltage insulators). The tube is usually mounted alongside the belt, and each hoop is connected to the steel ring closest to it; in this way the potential gradient is made uniform along both the belt and the ion gun.

At the "breech end" of the ion gun is the source of the ions we want to accelerate. A simple ion source is shown in Fig. 23. Electrons are emitted by a white-hot tungsten wire, usually spiraled like the filament in a motorcar bulb. The electrons are attracted toward the orifice on the left and many of them go through. However, on emerging they find themselves in the strong electric field of the ion gun and are driven back into the orifice. A slow stream of the gas to be ionized is admitted from the right. Some of the electrons hit gas atoms and knock off one (or more) of the atomic electrons, thus producing positive ions. Some of the ions produced in the orifice drift to the left, and are there gripped by the strong electric field in the gun and driven along at rapidly increasing speed. The design and operation of an efficient ion source is still somewhat of an art. It is not very difficult to get a stream of about 10^{14} (a hundred million millions) ions per second, but to get ten

times as much is an achievement of skill and patience.

It is important that the ions on their way along the gun do not encounter any obstacles. Air molecules, even in fairly small numbers, represent such obstacles; air therefore must be very completely removed, in other words, the gun must be very well evacuated. It is a big job in the first place to make the gun airtight; any cracks between adjacent rings (or elsewhere) must be completely closed by the use of gaskets or some special wax. But there is one leak we cannot stop—the gas flow which has to go through the ion source and without which there would be no ions for us to accelerate. Here a compromise has to be struck. The gas flow is made as small as we can without unduly reducing the production of ions, and several powerful pumps are attached to the ion gun so that the gas unavoidably entering is rapidly and continuously pumped away. The pumps are usually “oil diffusion pumps” in which the removal of air or gas is by a jet of oil vapor; this action is so fast that each gas molecule which enters the gun is pumped away within less than a second. Such pumps are made commercially and used in industrial enterprises, for instance, in the manufacture of lamp bulbs and radio tubes. Many physicists, however, prefer to have the pumps made in their own workshop, according to their own design.

If everything is well built and adjusted the ions form a narrow jet along the axis of the gun. The muzzle-end (in contrast to real guns) is of course closed to keep the air out, and the target is placed right inside the muzzle-end. The target is usually a metal plate on which is placed a thin layer of the element whose nuclei we wish to bombard. This metal plate is soldered to a pipe through which cold water is circulated; this is necessary in view of the heat generated by the impact of the ions. This heat would be

sufficient to make the metal plate red-hot if it were not water-cooled.

A machine such as this, with a belt and a gun some ten feet long, might be operated at a voltage up to about a million volts before sparks start developing. One way to go to higher voltages would be to build the whole machine on a larger scale, but the cost would increase rapidly. Another way, and a cheaper one, is to put the whole machine—belt, sphere, gun and all—into a large steel tank, which is then pumped up like a motorcar tire. As the air pressure is increased, the voltage can be raised higher and higher without sparks developing. A Van de Graaff machine which—without the tank—would give no more than one million volts can be operated smoothly at three or even four million volts if in compressed air, at a pressure of about 50 pounds per square inch, about the pressure in a well-inflated truck tire.

The Van de Graaff machines are a comparatively late development, and I have described them first because their operation depends on simple physical principles throughout. Electric charges are carried bodily, by means of a moving belt, up to a high electric potential, just as water may be carried up to a tower by a slow-moving chain of buckets;¹ they return in form of a narrow beam of fast-moving ions, like a sharp jet of water falling from a great height.

The arrangement by which the first transformation of nuclei with artificially accelerated ions was achieved differs from the one just described essentially only in the way the high electric potential was produced. At the time it was known how to produce voltages up to a hundred thousand

¹ Actually, the belt is run as fast as one dares, about 100 feet per second, but this is still a million times slower than the speed at which the ions strike the target.

volts for use in medical X-ray tubes. The method made use of a transformer to raise ordinary alternating current of, say, 220 volts to 50,000 volts, and then employed a couple of large rectifier tubes ("kenotrons") to convert the alternating potential into a steady one. All this is standard engineering practice and I won't go into details; the power pack in any A.C. radio is built on the same principle, only on a smaller scale. J. D. Cockroft and E. T. S. Walton (Cambridge, England) built a machine for 800,000 volts which consisted, crudely speaking, of eight machines for 100,000 volts each, piled on top of one another. However, they used an ingenious arrangement whereby the whole assembly could be run from a single transformer; this meant a considerable saving since the transformer is the most expensive item. Their ion gun and other parts were not very different from what I described above. This system and all sort of variants are still being used, particularly when the voltage required is no higher than a million volts. For higher voltages the Van de Graaff is a better machine, most people seem to agree.

The cyclotron works on a different principle, and a very ingenious one, which avoids the use of excessively high electric potentials and all the difficulties which they entail. The principle used is the principle of resonance, as explained on page 29, whereby a body can be set in vigorous motion by many small pushes and pulls, applied in the right rhythm. To make the application of this principle possible, the whole acceleration process is carried out in a strong magnetic field which forces the ions to run in circles. Hence the bulkiest and most expensive part of a cyclotron is a huge magnet. Its shape seems unusual for a magnet, but actually it is a logical development from a

pair of horseshoe magnets, as Fig. 24 may show you. Since the ions run in circles the pole pieces are made circular in shape. Cyclotrons have been made in a variety of sizes; a typical cyclotron magnet weighs fifty to one hundred tons and has pole pieces about three feet in diameter and a foot apart. Above and below the pole pieces there are large



FIG. 24. A cyclotron magnet has an unusual shape, for a magnet. However, it might have grown out of two horseshoe magnets, in the manner shown (although, of course, cyclotron magnets are not made that way!).

coils, wound from heavy copper strip and cooled by circulating oil or water. When we want to generate the magnetic field a current of several hundred amperes is passed through those coils, from a special dynamo in the room next door.

The "tank" which goes between the pole pieces is just being cleaned, so we can play with the magnet for a minute. You had better leave your watch on the table at the other end of the room while I start up the magnet; even non-magnetic watches stop in the strong magnetic field and sometimes go slightly wrong afterward. This deep purr you hear gradually rising in pitch until it becomes a steady whine is the noise of the dynamo starting up; it takes about a minute to reach full speed. You can come right close and put your hand between the pole pieces; you don't feel anything. But if you have steel keys in your pocket you can feel the magnetic field pulling at them. Here, take this screwdriver but hold it firmly in your fist. As you bring it closer to the magnet the pull becomes stronger and

stronger, and when you are close to the edge of the pole pieces you can hardly hold it back. Put your fist with the screwdriver right between the pole pieces, and the pull suddenly disappears. There the magnetic field is uniform all over and thus the screwdriver offers no resistance to being moved about, as long as it points up and down. But if you try to tilt it you will find that it resists as if its ends were held by strong springs. The force which tries to turn it back into the direction of the magnetic field is the same which makes the needle in a mariner's compass point north, only several thousand times stronger.

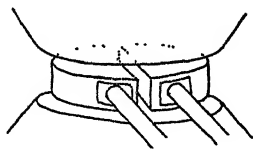
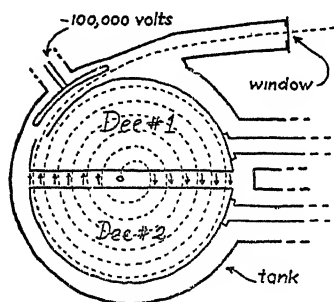


FIG 25. The dotted spiral line indicates the path of an ion as it is accelerated in a cyclotron (see text). The right-hand figure illustrates the position of the Dees between the poles of the magnet (compare Fig 24), here, the tank has not been drawn, in order not to confuse the picture.

Here come the boys with the "tank," so we had better turn off the dynamo; the whine gets deeper and deeper and eventually dies out. Now you can put the screwdriver close to the magnet and you won't feel anything; the magnetic field has gone.

The "tank" looks like a big pill-box, about three feet in diameter and nearly a foot high; its top and bottom are steel plates two inches thick, and the circular side wall is

$\frac{3}{4}$ inch thick brass. It has wheels attached to it and can be rolled into position on steel rails; otherwise it would be hard to handle as it weighs about a ton. Watch the boys push it into place and fix it with wedges so it can't shift when the magnet is turned on. It will take an hour before they are ready to run the machine; in the meantime I can explain how it works.

Inside the "tank" the ions are accelerated. There is an ion source close to the center, built rather like the one in the Van de Graaff, only of a more compact design. The electric field which accelerates the ions is produced between two hollow metal "Dees" (as we call them, because of their resemblance to a capital "D"). Their shape is best described by saying that together they form the two halves of a flat pill-box which has been sawed in two along its diameter. Each Dee is supported by a sturdy copper stem which leads to a big insulator. These insulators are commonly made of pyrex, a kind of glass used for ovenware, because of its ability to withstand sudden temperature changes, and also good at withstanding the rapid changes in electric field to which these insulators are exposed.

Now consider an ion running in a circle (forced by the magnetic field to do so), and let us assume that a potential difference of twenty thousand volts is applied to the Dees, the left one being positive and the one on the right negative. The ion spends half its time in the left Dee, half in the right Dee. Every time it crosses the boundary from left to right it becomes accelerated by the electric field between the Dees and gains twenty thousand electron-volts in kinetic energy.¹ On recrossing the line it gets slowed down and loses the energy it gained. This way we don't get anywhere.

¹ If it is a single charged ion. An alpha particle with its double charge gains twice as much.

The trick by which the cyclotron works is that we use a voltage which does not remain steady but changes direction several million times each second. Fortunately, the technique for producing such rapidly oscillating voltages has been developed by radio engineers, so all we have to do is to buy a good-sized radio transmitter and attach its output to the two Dees. By properly tuning the transmitter we can arrange that every time the ion arrives at the boundary between the Dees it gains twenty thousand electron-volts; the time it spends on its semicircular path in one of the Dees is just the time needed for the voltage to change direction and the ion is again accelerated when it crosses the line between the Dees. In this way the ion gains forty thousand electron-volts with every revolution, and an ion that has made a hundred revolutions has gained four million electron-volts in kinetic energy.

Of course an ion does not keep running in the same circle all the time. As it gains speed it is less deflected by the magnetic field and hence moves in a circle with a larger diameter; as a result the path of the ion is a kind of spiral made up of semicircles of gradually increasing size. Eventually it reaches the edge of the Dees, and this sets the limit to which the ions can be speeded up. This is the reason the magnet is made so large; the larger the magnet and the Dees, the greater the energy given to the particles before they strike the edge of the Dees.

I have so far taken for granted one thing which is very important and not entirely obvious. I have assumed that the ion takes a certain time to complete one semicircle and that this time interval remains constant as the ion gathers speed. There are two factors which influence this time interval. As the ion moves faster the semicircles get larger, and that in itself would make the time longer; but a faster

ion takes less time to cover a given distance. Actually, it turns out that the size of the semicircles and the speed of the ions increase in the same proportion, so that the time interval for one semicircle does indeed remain constant as the speed of the ions increases. Once we have tuned our transmitter correctly (and provided the magnetic field remains accurately constant) we can be sure that an ion, once accelerated, will keep in step with the oscillating electric field and will be accelerated every time it crosses the line between the Dees.

What happens to the ions when they reach the edge of the Dees? That depends on the kind of experiment we wish to make. Sometimes the target is placed inside the Dees, close to the edge; this arrangement causes a very intense bombardment of the target since each ion is bound eventually to hit it. In other cases we prefer to have the target in a more accessible position; we then provide a slit in one Dee through which some of the ions can escape. They are then guided by electric fields through a tube curved like the trunk of an elephant to a point several feet from the magnet where we can set up any equipment we like (for instance, a cloud chamber) close to the target. We can even get our ion beam out into the air by providing the end of the tube with a "window" made of metal foil, thin enough for the ions to go through. In air, the ion beam is visible if the room is somewhat darkened; it looks like a straight bluish flame about two feet long,¹ somewhat like the flame from a blowtorch, only fainter and quite steady and noiseless. When it strikes a solid body it heats it; you can light a cigarette by holding it in the beam. Don't put your finger in the beam; the burn you would get takes a

¹ The length is equal to the range of the particles and hence depends on their energy. Beams have been produced with a range of over ten feet.

long time to heal, because the beam penetrates through your skin into the tissues below. On the whole, the ion beam from a cyclotron is no toy for little children. If you stay close to it for more than a few minutes you may get sick from the large number of neutrons produced by collisions between the ions and all sorts of nuclei which they encounter. The cyclotron is operated entirely through remote control, by a man who sits in front of a control panel about 50 feet away. Furthermore, cyclotrons are often surrounded by a concrete wall or tanks full of water, to keep the neutrons from injuring people near by. On the other hand, the neutrons from a cyclotron, like the gamma rays from radium, can also have beneficial medical effects, and in several places medical research is in progress to determine the best use of neutrons for fighting disease, particularly cancer.

The inventor of the cyclotron is Ernest O. Lawrence, who started to experiment with a small model in 1927 and is at present busy building a mammoth cyclotron weighing four thousand tons, with pole pieces fifteen feet in diameter. With this monster he hopes to accelerate ions to energies of over a hundred million electron-volts. The one he built before (which is the biggest in operation) actually produces alpha particles of over thirty million electron-volts, about five times the energy of average natural alpha particles; their number is many thousand times greater than what you can get from the strongest natural alpha ray sources. Yet the natural sources are by no means beaten; there are cases where you prefer them to a cyclotron because they are small, portable, and reliable.

Before closing this chapter I should mention the latest machine of this kind, which is called the induction accelerator, or betatron. Its main part is also a large magnet, but

it accelerates electrons, not ions. The process by which the electrons are accelerated is difficult to make clear briefly; it depends on the fact that the magnetic field is not constant, the coils of the magnet being fed with alternating current. The first big machine of this kind started operation only in 1945. It accelerates electrons to an energy of about a hundred million electron-volts, and very interesting effects of these high-speed electrons have been reported, both in scientific circles and in the daily press. However, these results are still new and their bearing on the nature of atomic nuclei is still uncertain.

XIX

MASS AND ENERGY

WHEN COCKROFT and Walton built their 800,000 volt ion gun, they did not use it to make artificial alpha particles. Helium nuclei, carrying twice the charge of a proton, would have acquired an energy of 1.6 million electron-volts, less than a third of the energy which alpha particles of polonium possess. No, they used their gun to accelerate protons; these are really better bullets because their lower electric charge makes it easier for them to get close to an atomic nucleus. They used these protons to bombard lithium and at once their zinc sulphide screen began to sparkle. By inserting foils in front of the screen they found that the particles making the screen sparkle had a penetrating power equal to that of alpha particles of nine million electron-volts, and it was shown by magnetic deflection experiments that they actually were alpha particles.

Let us draw up the balance sheet for what happens here. A proton collides with a lithium nucleus. We shall tentatively assume that it is a nucleus of the more common isotope lithium 7. On the side marked "In" we have 4 charge units (1 from the proton, 3 from the lithium nucleus) and 8 mass units (1 from the proton, 7 from the lithium nucleus). On the side marked "Out" we have so far one alpha particle, a helium nucleus containing 2 charge units and 4 mass units. This leaves us with 2 charge units and 4 mass units, just enough to give another alpha particle.

So it appears that the collision of the proton with the lithium nucleus results in the formation of two helium nuclei which fly apart with considerable violence. If this picture is correct the alpha particles should occur in pairs, the two helium nuclei flying in opposite directions. That this was indeed the case could be shown with the help of the cloud chamber. A number of cloud-chamber photographs were made which showed just two tracks of equal length, pointing in directions opposite that of the lithium target. This shows that we were right in assuming that our alpha particles came from collisions of protons with the heavier lithium isotope, lithium 7; otherwise the two fragments would be of different weight and the tracks would not have the same length.¹

So our balance sheet seems to tally. Does it really do so exactly? The charges presumably do, since they simply correspond to four protons on each side of the balance sheet. The mass balance should be all right too, since there are again just four neutrons and four protons on each side. Still, we might check it. The masses of all the nuclei concerned—hydrogen, helium, lithium 7—can be measured by the magnetic deflection of their ions. In principle this can be done with the apparatus described in Chapter XIII. In practice, however, this apparatus is not accurate enough.

An arrangement with which really accurate measurements could be made was first built by the Englishman G. H. Aston. The luminous spots which the various kinds of ions made on our screen in Chapter XI were always somewhat blurred and their location could therefore not be measured very accurately. This blurring is due to two causes. First of all, the ions which come out of the ion gun

¹ The lighter isotope, lithium 6, can also be disintegrated by proton impact, but the resulting nuclei are much less penetrating.

do not all run in exactly the same direction. This can be improved by providing the ion gun with a very fine exit slit, and using another fine slit to pass only those ions moving in an accurately determined direction. Secondly, the ions coming out of the gun do not all have quite the same speed, and the faster ones get less deflected in the magnetic field. In this way ions having the same mass are somewhat scattered. Aston managed to get those ions together again by the ingenious trick of using an electric field which bends them in the direction opposite that which they get afterward in the magnetic field. It is possible to do this and still keep ions of different masses separate. Figure 26 gives a rough idea of the arrangement of electric and magnetic fields and of the tortuous path of the ions. Because of the use of fine slits and the long distance (several feet) the ions have to travel, far too few arrive at their final meeting-point to permit the use as before of a luminescent screen for their detection. Instead, Aston used special photographic plates containing little or no gelatin and very sensitive to ions, but unfortunately also very delicate and difficult to handle. If one exposes such a plate for some minutes or hours (as the case may be) to the ions of a certain element in Aston's apparatus and then develops it, each kind of ion shows up as a fine black line, and the whole plate resembles the kind one gets by photographing the spectrum of a neon lamp (see Plate 1). For this reason the arrangement of black lines on the plate (see Fig. 26) is commonly called a "mass spectrum" and Aston's instrument is called a *mass spectrograph*.

As far as I know there exist less than half a dozen mass spectrographs for high-precision work. Few physicists are attracted to the kind of work which requires infinite patience, painstaking care and unceasing self-criticism, and

does not extend any prospect of sensational discoveries. But to those who did undertake this toil we owe a great debt, as you will see in a moment.

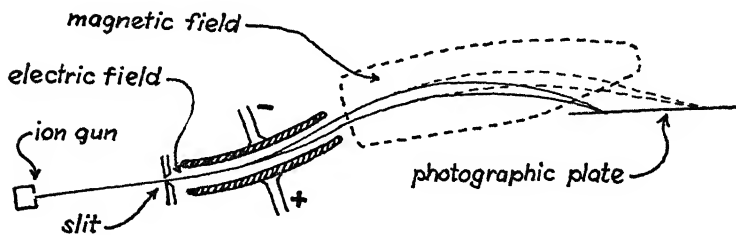


FIG. 26. Schematic diagram of a mass spectrograph according to Aston. The full and the dotted lines represent the paths of two different kinds of ions; ions of the same kind but of different speeds are seen striking the same spot on the photographic plate.

In precision measurements of this kind one does not use the weight of the hydrogen atom as a unit but, rather, one-sixteenth of the weight of an oxygen atom. This habit was introduced by the chemists, who pointed out that oxygen was a better standard than hydrogen because most determinations of atomic weight really boiled down to a comparison of the unknown atom with that of oxygen (oxygen forms stable and well-defined compounds with nearly all elements while hydrogen does not). At the same time they did not want to break entirely with the older idea of using the weight of the hydrogen atom as a standard and, since oxygen is very nearly 16 times heavier than hydrogen, they compromised by taking one-sixteenth of the weight of an oxygen atom as a unit.¹

If one uses this unit the atomic weight of hydrogen turns

¹ Later it was found that oxygen has a rare isotope with an atomic weight of about 18 (there is also an exceedingly rare oxygen 17 which we can disregard here). Since about one in 500 oxygen atoms is an atom of oxygen 18, the average weight of an oxygen atom is a little greater than the weight

out to be 1.0081, that of helium is 4.0039 and that of lithium 7 is 7.0182. Now we can check our balance sheet referring to the "nuclear reaction" in which a proton and a lithium 7 nucleus combine to form two alpha particles. On one side of the sheet we have the mass of a proton, 1.0081, plus the mass of a lithium 7 nucleus, 7.0182, which gives 8.0263. On the other side we have the mass of two helium atoms, or $2 \times 4.0039 = 8.0076$. The difference between the two results is small, but far too great to be explained away by errors in the weights of hydrogen, helium or lithium 7. The balance does not tally; 0.0185 mass units have been lost.

This is disturbing. We have all learned at school that the weight of matter remains unchanged however much it may change in constitution. A burning candle gets only apparently lighter; it consumes oxygen and produces water vapor and carbon dioxide. If you include all these products (for instance, by burning the candle inside a large airtight bottle and watching the weight of the bottle), you will find that the total weight does not change while the candle burns. A great many chemical reactions were carefully tested in this respect and it was always found that the end products weigh the same as the chemicals from which one starts. In our nuclear reaction, however, we find that the end products—two helium nuclei—weigh less, by about one-fifth of one per cent, than the proton and the lithium nucleus and the proton from which we started. Could it be that some small amount of matter got away unnoticed?

There is no need to make such an assumption. On the

of an atom of oxygen 16. In mass spectroscopy one naturally wants to use a definite isotope for a unit, while the chemist prefers a unit based on the average weight of the atoms of an element. We shall here use the mass spectroscopic unit, that is, one-sixteenth of the weight of an atom of the main isotope of oxygen.

contrary, everything is in perfect order. We merely forgot, on the side marked "Out" on our balance sheet, to include the kinetic energy of our two helium nuclei, 18 million electron-volts in all.

Back in 1905 Einstein showed that certain experiments (notably one performed by Michelson and Morley) forced us to revise some of our ideas about space and time. These revised ideas, together with the conclusions one had to draw from them, became known as the "Theory of Relativity." One of the conclusions Einstein drew was that whenever a material body gains or loses energy it also gains or loses weight. More briefly, one might say that *energy has weight*. Einstein showed that in order to find out how much a given amount of energy weighed one had merely to divide it by the square of the speed of light.

Let us figure how much the kinetic energy of our two helium nuclei weighs. It is convenient to start from the other end and to calculate first what amount of energy would have the same weight as a proton; to do this we have to multiply the weight of the proton by the square of the speed of light, which gives us $1.67 \times 10^{-24} \times 3 \times 10^{10} \times 3 \times 10^{10} = 1.5 \times 10^{-3}$ erg (0.0015 erg). Usually we express nuclear energies in electron-volts rather than in ergs; one electron-volt is equal to 1.6×10^{-12} erg (see page 188). So our 1.5×10^{-3} erg is the same as 9.4×10^8 electron-volts, or 940 million electron-volts. This then is the amount of energy which weighs as much as one proton. Hence one million electron-volts weigh $1/940$ of a proton, and the kinetic energy of our two helium nuclei (18 million electron-volts) has a weight of 0.0194 times the weight of a proton, just about the amount of weight that was missing. It is even a little too much, but we have forgotten to subtract the weight of the 800,000 electron-volts which the

proton brings along, having acquired that energy in the ion gun; this weight, about 0.001 times the weight of the proton, has to be entered on the other side of our balance sheet. If that is done the balance tallies quite accurately.

You see how important that is. If we know the masses of all the nuclei concerned in a certain reaction—both of those which enter the reaction and of those which result from it—then we can calculate beforehand how much energy the reaction is going to liberate. We can, for example, predict how much energy is liberated if the light lithium isotope, lithium 6, is hit by a proton, with the subsequent formation of two helium nuclei of mass 3 and 4, respectively. The mass of the helium 3 nucleus is known, it is 3.0170; added to the 4.0039 of the helium 4 nucleus this gives 7.0209 for the combined mass of the two resulting nuclei. On the other side we have the proton, mass 1.0081 and the lithium 6 nucleus, mass 6.0170, together 7.0251. Thus the resulting nuclei are again lighter than the ones from which we started, this time by only 0.0042 times the weight of a proton, which corresponds to the liberation of only four million electron-volts. From this energy we can calculate the penetration powers of these two unequal helium nuclei, and particles with just the powers calculated have indeed been found when lithium was bombarded with protons, together with the more penetrating ones which come from lithium 7.

On the other hand, the method can also be used to determine the accurate weight of the neutron. I told you before that neutrons are produced when beryllium (charge 4, mass 9.0150) is bombarded with alpha particles (helium nuclei, charge 2, mass 4.0039). The result is a neutron (charge 0, mass to be determined) and a carbon nucleus (charge 6, mass 12.0038). The energy of the alpha particles is known

and the energy with which the neutrons come out can be measured,¹ so we can calculate how much energy is liberated in the reaction, which turns out to be 5.8 million electron-volts. You can check for yourself (if you like) that the balance will tally only if the neutron has an "atomic weight"² of 1.0089. Other reactions in which neutrons are liberated can similarly be used to calculate the weight of the neutron, and the various results agree pretty well. So you see, the neutron and the proton weigh very nearly the same; the neutron is just a little bit heavier.

Sometimes the total weight of the resulting nuclei is larger than the total mass of the nuclei with which we start. In this case the reaction does not liberate energy, but consumes energy, and in order to make it possible at all we must supply the energy required. For instance, if we want to liberate neutrons by collisions between helium and nitrogen nuclei we have to supply 5.3 million electron-volts; if we bombard nitrogen with alpha particles which have less than this energy we don't get any neutrons. The nucleus produced is a fluorine nucleus (charge 9) and from the weights of the other nuclei concerned, together with the amount of energy we had to supply, its weight is found as 17.0076. The only isotope of fluorine known to mass-spectroscopists has an atomic weight of about 19; so it seems we have just produced an entirely new nucleus, one

¹ For instance, with a cloud chamber filled with hydrogen. If you take many expansion pictures you sometimes get a track pointing straight away from the beryllium, the source of the neutrons. Such a proton must have received a hit right in the center, and like a billiard ball to which this happens, it must have received the whole energy of the neutron, while the latter was practically stopped. Hence if we measure the energy of such a proton, from the length of its track, we know the energy of the neutron.

² Since the neutron has no charge it cannot hold electrons and thus can never be the nucleus of an atom. All the same it is often convenient to treat it as a nucleus of atomic number (nuclear charge) zero.

not found in nature. I shall tell you more about this nucleus in the next chapter.

A nucleus of the main isotope of oxygen consists of 8 protons and 8 neutrons and has an atomic weight of exactly 16.00000 (because it is the standard for atomic weight measurements). If you add up the weights of the 8 protons and 8 neutrons you find 16.1368. So if you were able to take 8 protons and 8 neutrons and put them together to form an oxygen nucleus, the amount of energy liberated would weigh 0.1368 atomic weight units, that is, about 127 million electron-volts, or about 8 million electron-volts for every neutron or proton, on the average. Vice versa, if you wanted to take an oxygen nucleus completely to pieces you would find it very hard work; it would take an average of about 8 million electron-volts to remove any one proton or neutron. There must be some strong forces which pull the parts of a nucleus together and guarantee its stability.

We do not yet know much about those forces. They cannot be of an electrical nature, because attractive electric forces act only between particles of the opposite charge (one positive and one negative); but all the parts of the nucleus are either positive or uncharged. From various properties of nuclei we can conclude that the forces die off very rapidly with increasing distance between the particles, much more rapidly than electric forces do. This would explain why those "nuclear forces" (as we call them for lack of a better name) have never been noticed except inside nuclei. Only there do you find particles less than 10^{-12} cm apart, and this is supposed to be about the maximum range over which the nuclear force can exert an appreciable influence. It seems at present useless to speculate about the nature of those forces; several theories have been put forward, but

more accurate measurements are needed before we can decide which of them (if any) is the correct one.

Let us now try to build up an oxygen nucleus in two steps, by first building four helium nuclei and then putting them together. Four helium nuclei weigh 16.0156 atomic weight units; this is already considerably less than the 16.1368, the accumulated weight of the proton and neutrons from which we started, and 113 million electron-volts of energy are liberated already at this stage. The second stage liberates much less energy, only about 14 million electron-volts. (Together, of course, the two stages liberate 127 million electron-volts, just as we found before.) This suggests that the forces holding the two protons and two neutrons together in a helium nucleus are much stronger than those which tie the four helium nuclei together in an oxygen nucleus. Imagine an apartment house in which live four married couples, each with two children; you may say that it is inhabited by sixteen people, but you would give a better description by saying that four families live there. The families may be on friendly terms, and they may regret one's moving out, but the ties among members of one family are much stronger.

Let me pursue this analogy a little further. If a country becomes overpopulated people begin to think of emigrating, and often a whole family emigrates together. The same may be said to be true of nuclei. As we go up to higher and higher elements the "population pressure" within each nucleus becomes greater and greater. This pressure is essentially due to the mutual repulsion of the positively charged protons; it is held in check by the nuclear forces, but less and less so as we go to heavier nuclei. A single proton or neutron will think twice before it emigrates, because family

ties are hard to break; but a whole family, a helium nucleus, may well decide in favor of emigration.

Of course protons and neutrons do not really hold family councils. Whether or not a helium nucleus leaves the rest of the nucleus is purely a matter of energy balance. If in the process of emigration energy is liberated, then the process is possible and will take place. If energy is consumed the process cannot take place unless the required energy is supplied, as, for instance, by the impact of a proton supplied by a friendly physicist. In an oxygen nucleus the removal of a helium nucleus requires an energy of more than two million electron-volts, and therefore an oxygen nucleus remains stable indefinitely unless we supply this energy. In a polonium nucleus, however, the removal of a helium nucleus liberates 5.3 million electron-volts, and thus the process can take place without assistance from outside, and does. We have met those emigrating helium nuclei before; they are the alpha particles that helped us discover the atomic nucleus and made our watch dial glow in the dark. Each of them carries, in the form of kinetic energy, the 5.3 million electron-volts liberated in the process of emigration.

Let us consider the instant at which the alpha particle leaves the nucleus. At first the nuclear forces will try to hold it back, and the particle has to fight its way against them. Very soon the nuclear forces lose hold, and the particle now gathers speed as it is pushed away by the positive charges in the remaining nucleus. After a while it is so far away that even the electric forces have no more appreciable effect. From then on it coasts along, gradually losing its speed as it collides with electrons from other atoms.

The nuclear force which holds the alpha particle back is

the reason the particle does not emigrate at once. You may imagine the particle making many attempts at getting away before it finally succeeds. Actually, it would never get away at all if quantum mechanics did not help it. One can calculate the wave function of the alpha particle, taking into account the nuclear and electric forces which act on it, just as Schroedinger calculated the wave function of the electron in a hydrogen atom, taking into account the electric attraction of the nucleus which acts on it. If one does this one finds that the "wave field" is strong inside the nucleus but fades rapidly as one moves away from it. There is still a trace of it left beyond the range of the nuclear force, in the region where a helium nucleus would be driven away by the electric field of the nucleus. Now, each particle is a slave of its wave function, and if there is a trace of the wave function outside the nucleus there is a chance the particle may find itself there. It may be a long time before this happens; but when it happens the helium nucleus gets rapidly driven away by the positive electric charge of the remaining nucleus. The attempt to emigrate has at last succeeded.

About twenty different kinds of nuclei are known to be "alpha-radioactive," that is, they spontaneously emit helium nuclei. Each of them has its characteristic "half-life," which is the time in which just half of the nuclei have emitted their helium nucleus. For example, in polonium there is a fifty-fifty chance that the alpha particle will succeed in escaping from its nucleus within the next 140 days; if there are a great many polonium nuclei about half of them will emit an alpha particle within the next 140 days. The remainder consists of polonium nuclei still trying to emit a helium nucleus. The fact that they have been trying so long is of no help to them; each one still has only a fifty-fifty

chance of alpha emission in the next 140 days. The same is true of those (one-fourth of the original number) which are left after the second 140-day period. After 3×140 days one-eighth of the original number will be still left, after 4×140 days one-sixteenth and so on. You never know when a given polonium nucleus is going to emit its alpha particle; it may do so within the next second, or it may let you wait a year.

The heaviest of all nuclei found in nature is that of the heavy uranium isotope, uranium 238. It is alpha-radioactive so its stock diminishes gradually. However, its half-life is over four billion years, and the whole universe is probably not older than a few billion years¹ so that the stock which was created at the beginning of the world is not yet exhausted. If a nucleus of uranium 238 emits an alpha particle there remains a nucleus which has two charges less and is therefore an isotope of thorium, the element two numbers below uranium. This nucleus, too, is radioactive, with a half-life of about four weeks; and so is the nucleus which results from it, and the next one, and so on down the line until polonium. Polonium is the last of this long sequence; after it has emitted an alpha particle the remaining nucleus is an isotope of lead (lead 206), which appears to have a firmer hold on its alpha particles since none have been found to be emitted from it. Radium is the best-known member of the sequence, which is therefore called the "radium family." Radium has a half-life of about 1700 years, quite long by human standards; yet its stock would have been exhausted millions of years ago if new radium were not constantly being formed by the decay of uranium

¹ I am taking the astrophysicists' word for that; if you want to know more about these cosmic questions read George Gamow's book, "The Birth and Death of the Sun."

nuclei. This is why radium is always found together with uranium and has to be extracted from uranium ores. For the sake of completeness I should mention that there are two more radioactive families in nature. One starts from the lighter uranium isotope (uranium 235) and is called the actinium family. The other is called the thorium family because it starts from the main isotope of thorium (thorium 232) with a half-life of about twenty billion years;¹ the radiothorium on your watch dial belongs to this family.

Radiothorium is not the last member of the thorium family; it undergoes several transmutations before settling down as a stable lead isotope. This is the reason why I replaced it by polonium in the experiment described in Chapter II.

Not all radioactive nuclei transform themselves by emitting an alpha particle (a helium nucleus). Some of them emit something which was called a beta particle before its nature was recognized, and which is nothing but an electron. The emission of an electron from a nucleus is therefore called a beta process, and I shall need a whole chapter to tell you about these very peculiar processes.

¹ By counting the alpha particles from a given amount of thorium (or some other long-lived alpha emitter) one finds at what rate its atoms transform themselves; from this one can calculate how long it would take until half of them are gone, even if this time is far beyond the span of human life.

XX

THE MYSTERIOUS STRANGER

IN THE first place, it is very surprising that a nucleus should be able to emit an electron. Didn't we say that the nucleus is made of protons and neutrons only? Yes, that is the consensus, even though a nucleus occasionally sends out an electron. After all, any atom can send out light quanta, yet we do not assume that the light quanta are stored within the atoms. Instead, we assume that a light quantum is created, comes into existence, at the instant it is emitted. So why should not an electron be created at the instant the nucleus wants to emit one?

This concept of the creation of a material particle seems at first very revolutionary. But we have seen before that modern developments have tended to diminish the gap between light and matter, by showing that both have a particle aspect and a wave aspect. And an electron is very light; it weighs only $1/1840$ of a proton and hence only about as much as an energy amount of half a million electron-volts—not much energy for a nucleus.

Let me first present some of the experimental evidence. Out of the many different radioactive substances which make up the radium family we separate, by suitable chemical processes, a substance called radium E. It is a bismuth isotope (bismuth 210) which is radioactive, but does not emit alpha particles. If you bring it close to a zinc sulphide screen the screen will glow, but there will be no individual

flashes; if the particles it emits produce flashes at all they are too weak to be visible individually. The particles are much more penetrating than alpha particles, they go easily through several sheets of paper, and some of them will even go through the lid of a sardine can.

In a cloud chamber they produce tracks which can be seen and photographed. These are much thinner than the tracks made by alpha particles, and not so straight. If the cloud chamber is placed in a magnetic field ¹ the tracks are found to be curved in the direction of negatively charged particles. By measuring the electric and magnetic deflection of a beam of these particles one can measure their mass and in this way find they must be electrons.

The peculiar thing is that different cloud-chamber tracks do not have the same amount of curvature in the magnetic field, which shows that the different beta particles ² emitted from radium E do not all possess the same energy. With alpha particles this is different; all alpha particles from polonium have precisely the same kinetic energy, 5.3 million electron-volts. But radium E emits beta particles with all sorts of energies—some high, some so low that they are hard to measure—without any distinct preference for particular energy values. Most of them have energies below half a million electron-volts; particles of higher energies are progressively rarer and no particles at all are found with kinetic energies above 850,000 electron-volts. The energy distribution of beta particles has been measured for a num-

¹ For instance, between the poles of a magnet; but then the tracks are hard to see and to photograph. Instead, one often places a coil of wire around the chamber and passes an electric current through the wire, at the instant of the expansion. Since the current has to flow only for a second or less, one can afford to use a very strong current, which gives a strong magnetic field.

² I shall continue to use the term "beta particles" to indicate that the electrons of which I speak have been emitted from a nucleus.

ber of radioactive substances other than radium E; if one plots it on paper one always gets about the same curve, with a sharp upper energy limit beyond which no beta particles are observed, and a rounded maximum at some lower energy.

Why is the energy distribution of beta particles so different from that of alpha particles? Let us check the energy balance. This cannot be done with radium E because the weight of its nucleus is not known accurately enough. But there are some cases where we know accurately the weight both of the beta-emitting nucleus and of the nucleus left after the beta particle has been emitted. In these cases you always find the following result: the balance tallies for those electrons only which have the greatest energy; all other electrons have too little energy to make the balance tally.

What does a businessman do when his cash register does not tally? He counts the money again, carefully; he questions his salesman; he checks the mechanism of his cash register. If there is still money missing, he can't help thinking that it must have been stolen.

The physicists did the same. They repeated their measurements with greater care. They considered the possibility that the beta particles may have been slowed down, some of them, before their speed could be measured, and they had to dismiss this possibility. They tried to find flaws in their own reasoning. Eventually, after years of labor, they admitted that energy had indeed been unaccountably lost.

So they had to invent a thief. It had to be a pretty clever thief to elude all the nets physicists set up in order to prevent any known form of energy from escaping. He could not carry an electric charge or he would at once betray himself by making a track in a cloud chamber. He had to be very light, for there are some beta particles which almost

make the balance tally. This meant that sometimes very little energy was missing, or in other words, very little mass. He could not be a light quantum, for light quanta of that sort of energy are X-ray quanta and they would easily have been observed if there were any. It had to be a brand-new particle—very light (much lighter than an electron) and without electric charge—and it received the nickname “neutrino” (Italian for “the little neutral one”).

You will probably say that this story of the mysterious stranger sounds fishy to you. Has anybody ever seen him? No, I must admit, nobody has. And there are a great many physicists who refuse to believe in the existence of a particle which nobody has ever observed.

However, it is one thing to believe in the neutrino, and another to accept provisionally the assumption of the neutrino in order to see what would follow from such an assumption. The Italian physicist, Enrico Fermi, did just this. He argued that if the beta process consisted not just in the emission of an electron, but in the simultaneous emission of two particles, an electron and a neutrino, then in each beta process the available energy had to be divided up between the two particles. This division would not always be the same; sometimes the electron would get the bigger share, sometimes the neutrino, and occasionally each get about half. Fermi tried to calculate the way in which the division was likely to vary. He used the methods of quantum mechanics (wave mechanics) and whenever he had to make some specific assumption he tried to make the simplest one. The result was very gratifying: the energy distribution which the beta particles should have, according to his calculation, agrees very well with the distribution which they actually have, according to direct measurements.

This is obviously evidence in favor of the existence of the

neutrino, and some people think it is pretty strong evidence. Still, as long as nobody has actually observed a neutrino you are free to believe in its existence or not, as you like. So we shall now adjourn the court and postpone judgment until some future date when more definite evidence may be forthcoming.

I should like to point out that it is only in beta processes, that is, when an electron is emitted from a nucleus, that energy is found missing. In all other nuclear reactions, wherever a check is possible, the mass balance always tallies.

If a beta particle is emitted the weight of the nucleus changes by only a small fraction of the weight of one proton. But the charge of the nucleus increases by one unit because the electron is negatively charged; taking away one negative charge has the same effect as adding a positive one. So the nucleus contains, after the emission of the beta electron, one proton more and one neutron less than before. You may say, one of its neutrons has been converted into a proton, presumably because the nucleus had too high a proportion of neutrons.

The scope of research on beta radioactivity was increased enormously when it was found that one could artificially create nuclei in which the proportion of neutrons and protons was "wrong" and tended to readjust itself by the emission of beta particles. This discovery of artificial radioactivity by Curie-Joliot, in 1934, was one of the greatest single steps forward in our understanding of atomic nuclei.

I mentioned on page 195 that by bombarding nitrogen with alpha particles of sufficient energy one could liberate neutrons, with the formation of a nucleus of fluorine 17, an isotope not found in natural fluorine. But ordinary oxygen has an isotope 17, though it occurs only in very small quantities. The nuclear charges of oxygen and fluorine are

8 and 9 respectively. So the fluorine 17 nucleus has a higher charge than the oxygen 17 nucleus, and would have to transform one of its protons into a neutron in order to become an oxygen nucleus. The beta process which we described on the last few pages does just the opposite: it transforms a neutron into a proton. But the fluorine 17 nucleus knows what to do: it transforms one of its protons into a neutron and emits a *positron*, a kind of electron with a positive charge.

This is a particle which I have not yet mentioned. It is similar to an electron in every way; it has the same weight and the same amount of electric charge, only the charge is positive. If positrons pass through a cloud chamber they produce tracks which look just like electron tracks. But if the cloud chamber is in a magnetic field the electron tracks are bent one way and the positron tracks the other way; in this way it was discovered that they were positively charged.

The reason positrons had not been discovered earlier is that they are very rare and don't last very long. If a positron gets too close to an ordinary negative electron¹ a process takes place which is called annihilation. The two particles neutralize their electric charges and disappear; their mass is converted into energy, in the form of electromagnetic radiation (X-rays). It is easy to observe this radiation and to measure its wave length simply by measuring its penetra-

¹ The terminology is confused. Some think the term "electron" should embrace both positive and negative particles of the mass of $1/1840$ of a proton, and that they should be called positive electrons and negative electrons respectively. Others propose the names positron and negatron, with electron as a term which includes both. Still others think that the word electron should be reserved for the negative ones, this being their traditional name, the others to be called positrons; in this case there would be no common name for both. It is as with men and women; the word men is sometimes used to include members of both sexes, sometimes it means males only. Fortunately, this ambiguity does not usually prevent people from knowing what is meant.

tion power (in Chapter VI I told you that the penetration power of X-rays increases if their wave length decreases). From the wave length one can calculate (with the help of Planck's constant, see page 109) the energy carried by a single quantum of this radiation. In this way one finds that each quantum carries exactly half the energy created in the annihilation process, so we must assume that two quanta are emitted every time. It can indeed be shown experimentally that the radiation consists of quanta emitted in pairs, the two quanta in each pair going in opposite directions, like the two alpha particles emitted when a lithium nucleus is hit by a proton (see page 188). One can also show why always two quanta should be emitted. When an atom emits a quantum it recoils just as a gun recoils when it is fired. But when a positron and an electron become annihilated there is nothing left to recoil from the radiation quantum; therefore two radiation quanta have to be emitted, each one of them taking up the recoil from the other.

The opposite process, the conversion of radiation energy into electrons and positrons is also possible. It is not feasible to aim two radiation quanta accurately at each other and thus to produce a positron and an electron (which would be the exact reverse of the annihilation process just discussed). But if X-ray quanta with sufficient energy pass through matter their interaction with the strong electric fields in the immediate neighborhood of atomic nuclei has the same effect that the collision of two quanta would have; occasionally one observes the simultaneous birth of two electrons, one positive and one negative. I can show you a cloud-chamber picture of such a newborn pair; the chamber was in a magnetic field and you can see that the paths of the two particles bend in opposite directions, which demonstrates that they carry opposite charges. (Plate 7.)

All these phenomena are manifestations of Einstein's equivalence of mass and energy which we first met (on page 193) when we tried to balance the masses and energies involved in the transformation of an atomic nucleus. There we found that the total mass of the nuclei involved is a little smaller after the reaction than it was before, and that the difference is just the amount of weight which, according to Einstein's formula, has to be ascribed to the amount of energy liberated in the reaction. We may say that a small fraction of the mass of the nuclei concerned has been converted into energy (kinetic energy in this case). In the mutual annihilation of positive and negative electrons we have a more drastic example of the conversion of matter into energy, since the two electrons disappear completely, and nothing but radiant energy is left. Of course you might claim that light quanta are in a sense still material particles; but they are quickly absorbed and their energy is converted into heat, which is undoubtedly a form of energy. On the other hand, some people like to say that matter is merely a form of energy, and that the annihilation of electrons and positrons or the creation of electron-positron pairs out of radiation are merely instances of the transformation of energy from one form into another, a very familiar phenomenon. To the physicist these differences of opinion are not very important. He is concerned with experimental facts and sensible ways of interpreting them. Questions such as "What is the ultimate nature of matter and energy?" do not fall within his province, although his results sometimes serve to eliminate certain proposed answers to such questions.

Let us now return to our beta processes. We see now that there are two kinds of them: a neutron gets transformed into a proton under emission of a (negative) electron, or

a proton gets transformed into a neutron, with the emission of a positron. If only the first kind existed one might think that the neutron is essentially a proton which has "swallowed" an electron; but the existence of the second kind of beta transformation would seem to indicate that it is the other way round, that the neutron is fundamentally the simpler particle and that the proton is composed of a neutron and positron. In view of this ambiguity, the following compromise has been suggested and is fairly generally accepted. The proton and the neutron are regarded as different states of the same particle, called a nucleon; a beta transformation is a transition from one state to the other and is possible in either direction. Using this terminology we may say that the fluorine -17 nucleus consists of 17 nucleons of which 9 are protons and 8 are neutrons; the transformation of one of the protons into a neutron—with the emission of a positron—liberates energy and can therefore take place. A nucleus of radium E consists of 210 nucleons, of which 83 are protons and 127 are neutrons; here transformation of a proton into a neutron would consume energy, but the inverse process, the conversion of a neutron into a proton, liberates energy, and therefore radium E is beta-radioactive and emits (negative) electrons. Some nuclei have just the right proportion of protons and neutrons, and in this case a beta transformation either way would consume rather than liberate energy. These nuclei are stable, and from them are made the stable elements which we find in nature.

Just what the right proportion of protons and neutrons is depends on a number of things. Some rough rules can be found by looking at a list of stable isotopes. Light nuclei have an equal number of protons and neutrons, or a small excess of neutrons. As you go to heavier and heavier nuclei

the neutron excess tends to get greater and greater. This can be understood since it is mainly the protons which—because of their mutual repulsion—tend to increase the “population pressure” while the neutrons are more sociable. Therefore the nucleus tends to relieve its population pressure by converting some of its protons into neutrons. On the other hand, the neutrons have a strong tendency to combine with protons so as to form alpha particles consisting of two protons and two neutrons each (see page 169). This tendency explains why light nuclei tend to have equal numbers of protons and neutrons as well as why heavy nuclei convert only part of their nucleons into neutrons, and not all of them. There are a great many peculiarities in the distribution of stable isotopes which are not yet fully understood; they offer clues concerning the forces acting between neutrons and protons in the same way as the layout of a prehistoric settlement allows the archaeologist to draw certain conclusions regarding the social habits of the people who once inhabited the place.

Nearly three hundred stable isotopes are known, and a similar number of unstable isotopes have been produced by nuclear transformations, since 1934, in addition to several dozen unstable isotopes which are found in nature. Their properties, such as their half-lives and the energies of the particles which they emit, are being intensively studied. Our knowledge of nuclei is at present in a state comparable to our knowledge of atoms forty years ago, when much was known about properties of atoms (for instance, the spectral lines they emit, or their chemical affinities), while there were only the hazy beginnings of a theory which could explain those properties. We have at present only very hazy ideas about the way the nucleons are arranged in an atomic nucleus. They appear to be very

closely packed together; they are probably not arranged in shells like the electrons in an atom. In ten years we shall probably know a lot more about the structure of atomic nuclei.

We can now explain a fact which was a bit puzzling previously. I told you that by lining up the elements in order of increasing atomic weight the chemists got an arrangement (the "periodic system") in which similar chemical properties repeated themselves in a regular fashion. We saw later that such a periodic behavior was explained by the shell structure of the electrons in the atoms (see page 159) if the elements were arranged according to their atomic number. Now the atomic weight is the average number of nucleons, while the atomic number (nuclear charge) is the number of protons. Since the proportion of protons does not vary much from one element to the next it is not surprising that one should get nearly the same arrangement of elements, whether one uses the atomic weight or the atomic number. Nor is it surprising that there should be a few discrepancies between the two arrangements.

Let me briefly summarize the contents of this chapter. Nuclei consist of protons and neutrons which are regarded as different states of one particle, called nucleon. For a given number of nucleons in a nucleus there should be a certain proportion of neutrons and protons. If a nucleus has too many protons, one of them may become converted into a neutron, with the simultaneous emission of a positive electron (positron); similarly a nucleus with too many neutrons can convert one of them into a proton, at the same time emitting a (negative) electron. In these so-called beta processes some energy is usually lost; to account for this loss one assumes that together with the (positive or negative) electron a neutrino is emitted, a hypothetical particle

with no electric charge and very small mass which escapes all known methods of detection. There is some evidence in favor of the existence of such a particle, but nothing that can be called proof.

Positive electrons only last a small fraction of a second. If a positron gets close to an ordinary electron the two annihilate each other and become converted into energy in the form of two X-ray quanta. The opposite process, the conversion of a sufficiently energetic X-ray quantum into an electron pair (one positive and one negative electron) is also possible, by interaction with the strong electric field in the immediate neighborhood of an atomic nucleus.

XXI

ATOMIC POWER

WHAT HAPPENS when a candle burns? First, you have to apply a match, in order to melt and vaporize some of the paraffin. The paraffin molecules in the vapor then combine with oxygen molecules and oxidize, forming carbon dioxide and water vapor. In this process enough heat is developed to vaporize more paraffin and thereby to keep the reaction going until the candle has burned down.

If you open a gas tap you do not have to vaporize your fuel, it is already gaseous. All the same you need heat (for instance, from a lighted match) to start the oxidation process, to ignite the gas. The chief reason is that the oxygen in the air is in the form of molecules, each consisting of two atoms which hang together quite firmly. You have to employ energy to separate two of these atoms before they will interact with a molecule of your illuminating gas; but once you have done this enough energy is liberated by the oxidation to decompose more oxygen molecules and then the reaction can not only support itself but also spread rapidly through the gas mixture, causing an explosion. You know how the gas pops if you let it escape for a few seconds before applying a match.

It is easy to determine the amount of energy liberated in the burning of a certain amount of fuel, for instance, by observing how much has to be burned to bring a given quantity of water to a boil, in an arrangement where all the heat is

utilized. If one then divides this energy amount by the number of fuel molecules in the amount burned one gets the energy per fuel molecule. This energy is found to be on the scale of one or two electron-volts, for most fuels.

This amount sounds reasonable to the atomic physicist. All chemical reactions are due to the rearrangement of the outermost electrons of the atoms, and since it takes about 10 to 20 electron-volts to remove one of those electrons it is plausible that a moderate fraction of this energy may be lost or gained in their rearrangement due to the close approach of another atom. In some cases this energy can be calculated from atomic data. For example, if you burn metallic sodium in chlorine gas you get sodium chloride, our old friend. You can analyze this reaction into the following steps: First you vaporize the sodium, investing a certain amount of heat which you can measure. Then each chlorine molecule has to be decomposed into its two atoms, which takes a certain amount of energy. An electron has to be removed from each sodium atom; the energy required (6.5 electron-volts) can be measured by the method described on page 101. So far we have invested energy; now we can begin to cash in. Each of the electrons we took away from the sodium atoms is now added to a chlorine atom, liberating some energy (though not as much as it cost us to get the electrons off the sodium). Finally all the positive sodium ions and negative chlorine ions are put together to form a sodium chloride crystal. This again liberates energy, because of the mutual attraction of the neighboring oppositely charged ions, and since we know their distance (see page 70) it is easy to calculate how much energy is liberated as one ion after another drops into its place. The whole process is like a close business transaction; you have to sink a lot of money in order to make a small profit.

When radioactivity was discovered it very soon became clear that here there were vastly greater energy sources. An atom of polonium liberates an energy of 5.3 million electron-volts, about three million times more than a molecule of an average fuel. But for practical energy production the radioactive elements were useless. Those which disintegrate fairly rapidly (like polonium) are available in minute quantities only, and those of which tons can be had, like uranium and thorium, take billions of years to give off their energy, and there was no way of hustling them.

When Rutherford found, in 1917, that the nitrogen nucleus could be transformed by impact of an alpha particle and that the emerging proton carried more energy than the impinging alpha particle, hopes began to rise again. Here was a way of causing, at will, reactions between atomic nuclei. Since these nuclear reactions liberate millions of times greater energies than chemical reactions (reactions not between nuclei but between atoms) the age of plenty seemed to be around the corner, when a handful of "nuclear fuel" would drive a liner across the ocean and people would no longer have to work in coal mines or oil fields.

The trouble was that for each alpha particle which hit a nitrogen nucleus, about a million alpha particles were wasted. Since there is no way of aiming an alpha particle at a nucleus this waste was unavoidable and made the process completely uneconomical as a means of producing energy. Apart from that, the amounts of energy which could be liberated in this way were ridiculously small. Even if you use a cyclotron you can liberate barely enough nuclear energy to run a flashlight from it, and you have to use many thousand times more energy in accelerating your ions.

People then began to discuss the possibility of a nuclear chain reaction similar to the chemical chain reactions which

occur, for instance, when a candle burns. Couldn't one utilize the energy liberated in the transformation of one nucleus for "igniting" another nucleus, and so on? For a long time this seemed impossible. True, a few of the protons liberated in the transformation, say, of nitrogen, might themselves hit some other nucleus, causing it to liberate more energy, but most of them were wasted.

Then the neutron was discovered and hopes went up again. For, neutrons don't get wasted, they go on and on until they hit a nucleus. Incidentally, this property of neutrons suggests a very simple way of measuring the size of nuclei. If you place a copper sheet across a beam of neutrons, most of them, but not all, are found to go through the sheet. It is easy to work out, from the known number of copper nuclei in the sheet, how many neutrons would be intercepted if the nuclei had a certain size, and one can adjust this size until one gets agreement with the number of intercepted neutrons experimentally determined. Such measurements have been made upon nearly all elements and it was found that the size, or more accurately the volume, of nuclei increases in proportion to their atomic weight, that is, to the number of nucleons. This supports the idea that the nucleons in a nucleus are closely packed together, like potatoes in a sack.

But let us return to the problem of atomic power. Neutrons don't get wasted, but that does not eliminate all wastage. For in order to produce neutrons, we have to bombard nuclei with alpha particles or other charged particles such as protons, and most of them get wasted. What we would need is a nuclear reaction caused by a neutron and resulting in the emission of a neutron, together with the liberation of energy. It would indeed be preferable that the reaction should result in the emission of more than one

neutron, since a small amount of wastage is unavoidable even with neutrons, and we don't want the chain to break off every time a neutron is lost. And, of course, the energy liberated should be as large as possible.

Just such a reaction was discovered early in 1939. Clues which might have led to this discovery had been known since 1936, but although some of the best chemists and physicists in Italy, France, and Germany worked on them they were misunderstood for over two years. The work was concerned with the new radioactive elements which could be made from uranium by bombardment with neutrons. It was assumed—by analogy to numerous results with other elements—that the neutron becomes attached to the uranium nucleus, with the emission of, at most, an alpha particle. However, it was very hard in this way to explain the bewildering variety of radioactive elements, with different chemical properties and different half-lives, found in uranium which had been bombarded by neutrons. In the end O. Hahn and F. Strassmann, in Germany, ascertained the chemical nature of one of those radioactive products and found, to their great surprise, that it must be an isotope of barium.

The atomic number of uranium is 92, but that of barium is only 56. So here a nucleus has indeed been split right across, not just nicked. The reason this is possible with uranium lies in the mutual repulsion of its protons. I spoke on page 197 about the "population pressure" which in heavy nuclei gets so large that it frequently causes the "emigration" of alpha particles. In the very heaviest nuclei, uranium and thorium, this pressure grows so strong that it needs only a small stimulus—such as the impact of a neutron—for the nucleus to divide itself in two, in the same way as a large

drop of water on a greasy surface divides when shaken. Once separated, the two fragments are driven apart by their electric repulsion and acquire a kinetic energy of nearly 200 million electron-volts (together). This process became known under the name of nuclear fission.

The numbers of nucleons in the two fragments are not always the same and that explains the great variety of radioactive products which had been found. I told you before, on page 210, that lighter nuclei require a smaller proportion of neutrons than heavy ones. Now the freshly made fragments still contain the same proportion of neutrons as the original uranium nucleus.

In view of their smaller weight, this proportion is too high for them. Some neutrons fall overboard in the violent commotion immediately after the splitting of the nucleus, and these are the ones which make it possible to produce a chain reaction. Yet, afterwards, the fragments still contain too many neutrons and proceed to convert some of them into protons, by the beta processes described in Chapter XX. This is the reason for their radioactivity.

By the summer of 1939 it was known that more than one neutron, on an average, was sent out in the process of nuclear fission, and the possibility of a nuclear chain reaction was becoming tangible. But there still were great difficulties. In order to cause fission in uranium 238 (which makes up more than 99 per cent of ordinary uranium) the neutrons had to have a considerable kinetic energy, on the scale of a million volts or more; neutrons of lower energy were wasted. The rare isotope uranium 235 is more easily split, even by neutrons of quite low speed; very slow neutrons are even particularly good at it. Consequently, it was possible to cause a chain reaction in two ways. One was to

mix the uranium with some light element in which the neutrons would quickly get slowed down¹ so that they would be able to cause fission in the nuclei of uranium 235. This turned out to be a touch-and-go affair but was eventually made to work. Pure carbon in the form of graphite was found to be the most practical material for slowing the neutrons, and the big "graphite piles" in Hanford are producing large amounts of power, though not in an industrially useful form. The other way was to separate large amounts of the uranium isotopes, a stupendous job which few people before this war would have thought possible, but this, too, was accomplished.

It would be entirely outside the frame of this book to try to tell you about the details of the work which led to the successful construction of atomic bombs. The book, "Atomic Power for Military Purposes," by H. D. Smyth, will tell you all that you want to know, as far as it can be told at present. Here I shall only point out a few more things which may help you to get a balanced outlook on things to come.

Don't expect a pill of uranium 235 to drive your car for a year. It would contain enough energy to do that, but you would not be able to get it out. A neutron originating in such a pill would have only a small chance of encountering a nucleus before getting out of the pill, and even though neutron reflectors can be arranged² not enough neutrons could be made to cause fissions in the pill to keep the reaction going. And even if you had enough money to buy a

¹ Every time a neutron rebounds from a nucleus the latter is set in motion and the neutron, accordingly, loses some energy. The lighter the nucleus, the more energy is lost.

² There are no mirrors for neutrons. But a thick plate of almost any solid material will reflect some neutrons because they collide with nuclei in the material and some of them are turned back by such collisions.

“pill” large enough to support a chain reaction I would not advise riding in such an “atomic car.” Some of the neutrons are always bound to escape from the uranium reactor, and as I told you on page 186, neutrons can have bad effects on the human body; a few minutes’ ride in this car would be enough to kill you. One can surround the reactor with a shield which will prevent the deadly radiations from reaching you, but such a shield would have to weigh many tons to give sufficient protection, and it could not be carried on a motor car. Seagoing ships are another story; there the weight of the shield may well be less than the weight of coal or oil fuel needed nowadays.

Power stations running on atomic power¹ are likely to be developed earlier than mobile nuclear generators. In power stations the shielding presents no great problem, and they could be placed far from inhabited places since, at least in the beginning, the possibility of an explosion could not be entirely disregarded. Many engineering problems have yet to be solved before power can be produced in an industrially useful form, and economically. After all, the fuel cost represents only part of the cost of power; even if the fuel costs practically nothing the investment is very considerable and it is not even certain whether atomic power will be able to compete with other forms of power. River water is free to everyone, yet water power costs money and has not ousted the power stations which burn coal. I think it will be at least five years before even experimental atomic power stations operate, and ten years before one can judge their possible economic importance.

Yet benefits to humanity may accrue much sooner,

¹ Nuclear power or sub-atomic power would be more appropriate terms. After all, forces between atoms are responsible for power produced from coal or oil.

mainly from the radioactive substances which can be produced. In the first place, there are the fission products themselves, comprising active isotopes of about twenty elements. In addition, one can irradiate any element one likes with the surplus neutrons of the chain reactor and thereby make additional radioactive substances which do not occur among the fission products. Many uses for these substances will no doubt be found when the world at large becomes aware of the possible supplies. One very important application of radioactive isotopes is their use as "tracers" in studying the behavior of certain elements in the human body. An example will best show you how tracers are used.

The red blood corpuscles contain iron, and food must contain iron so that the body can produce new blood all the time. In cases of anemia (low number of red blood corpuscles) it may be desirable to give iron to the patient. But in what form? Some iron compounds are poisonous, some are indigestible and leave the body without doing any good. Is there a quick way of testing iron compounds? With radioactive tracers, this is easy. One makes the compound in question out of iron to which has been added a very small amount of a radioactive iron isotope. After giving this compound to a patient (if one is sure it is not poisonous!) one takes several blood samples, at suitable time intervals, and carefully measures the radioactivity of each. The radioactive iron has the same chemical behavior as ordinary iron; if a sample is active it shows that a proportionate amount of iron from the compound has actually entered the blood. By comparing the different blood samples one can also get a pretty good idea how long it takes. By measuring the radioactivity of the excretions we can also find out how much of the iron is not retained by the body. If one experiments with animals one may kill the animal after some time and

find out how the iron has distributed itself through the body, simply by measuring the radioactivity of various organs. Without the radioactive tracer we could not get this detailed information because we would not be able to distinguish the particular iron from the iron already in the body.

You can easily see how important it is for the progress of medicine to get quick and detailed information about what the body does with medicaments, foodstuffs, etc. Important work of this kind has already been carried out with radioactive isotopes of carbon, phosphorus, calcium, iodine and other biologically important elements prepared mainly with the help of cyclotrons. I believe that nuclear chain reactions, by making large amounts of radioactive isotopes available to scientists of all kinds, may help to stimulate new lines of research in biology and medicine.

INDEX

- ABSOLUTE SYSTEM**, 81-91
Affinities of atoms, 78, 79
Alpha particles, defined, 173; formation of, 188, 189; properties of, 125 ff.; used to liberate neutrons, 194, 195, 206, 216
Alpha ray, 125 ff.
Alpha-radioactive nuclei, 199-201
Ampere, defined, 90, 91
Ampère, A. M., 90
Aston, G. H., 188, 189
Atom-building, 165
Atomic bomb, 220
"Atomic car," 220, 221
Atomic power, 214 ff.
Atomic number, 159
Atomic theory of chemistry, 64
Atomic weight, 3-5, 6, 7, 8, 60, 65-67, 113 ff.
Atom-smashing, 164, 165, 172
Atom-smashing machines, 173-187

BETA PARTICLES, 201 ff.
Betatron, 9, 54, 186, 187
Bohr, Niels, 9, 60, 111, 142-145, 152
Bothe, W., 170
Bragg, Sir William, 47
Broglie, L. de, 9, 148, 149, 152

CENTIMETER, DEFINED, 82
Centrifugal force, 140, 141
Cesium, defined, 106
C. G. S. system, 81-91
Chadwick, James, 164, 171, 172
Cloud chamber, operation of, 132-135, 168 ff., 189, 203, 207
Cockroft, J. D., 180, 188
Compass, and electromagnetic waves, 26-31
Complementarity, 111, 112, 155, 161
Conservation of energy, 84, 85
Continuous spectrum, 41
Counting atoms, method of, 11-16

Crystals, atomic structure of, 6, 17-25, 56
Cune, Irene, 170, 171, 172, 206
Cyclotron, 9, 132, 180-186, 223

DEES, OF CYCLOTRON, 183-185
Diffraction grating, 35-45, 57, 58, 101
Diffraction lines, 36
Diffraction of light, 22
Diffraction patterns, 23-25
Diffraction screen, 22-25, 35
Dirac, P. A. M., 154
Dyne, 83, 84, 87

EDISON, THOMAS A., 92, 93, 106
Einstein, Albert, 112, 193, 209
Electric field, defined, 31; in oil drop experiment, 75, 76, 77
Electricity, properties of, 86-91
Electrolysis, 69, 72, 75
Electromagnetic waves, 6, 26-34, 110-112, 141-146, 149
Electron, defined, 4, 5; Edison's experiment with, 92, 93; effect of magnet on beam of, 97-98; finding weight of, 96-100, 113 ff., 202; orbit of, 140 ff.; negative and positive, 203 ff.; properties of, 93-102
Electron gun, 93, 147
Electron waves, 147-161
Electron-volts, 101, 102, 103, 119, 120, 121
Electronics, 93
Electrostatic machines, 173, 174
Element, 60, 64, 122, 159-161
Energy, and light, 103 ff.; atomic, 214 ff.; conservation of, 84, 85; conversion of matter into, 209; defined, 85; equivalence of mass and, 189 ff., 209; of beta particles, 203 ff.; of photon, 104, 105
Erg, 84, 193

- FERMI, ENRICO, 205
- GALILEO, 84
- Gram, defined, 83
- Graphite piles, 220
- Gratings. See Diffraction grating
- HAFNIUM, 60
- "Half-life," of alpha-radioactive nuclei, 199-201
- Halogens, 158
- Harnson, 93
- Heat treatment of metals, 59
- Heisenberg, Werner, theory of, 154
- Helium atom, as source of alpha particles, 130, 131, 137; electrons in, 119, 120, 138; finding weight of, 118-120
- Hefsey, 60
- Hydrogen atom, Bohr's model of, 145, 146; electrons in, 120; finding weight of, 77, 78, 115-118; nucleus of, 140 ff.
- INFRARED LIGHT, 105, 106
- Infrared ray, 40
- Insulin molecule, atoms in, 67, 68
- Interference, defined, 29, 30
- Ionization, 69-72; of atom, 101, 102
- Ions, 5, 6, 7, 72, 69 ff.; in cyclotron, 183-186; in Van de Graaff machine, 177-180
- Ion gun, 115-123, 174, 175
- Isotopes, 8, 122, 123, 162, 163, 211, 212
- JOLIOT, FREDERIC, 170, 171, 172, 206
- KEKULÉ, 65
- Kenotrons, 180
- Kinetic energy, defined, 85
- LAUE, 47
- "Laue Pattern," 20-23
- Light, nature of, 32, 103-112
- Light quanta, 104, 105, 106, 202, 205
- Light waves, 103-112, 148
- Lithium atom, electrons in, 121, 123; weight of, 120, 121
- MAGNET, EFFECT ON ELECTRON BEAM, 97, 98
- Magnetic field, 27-34; of cyclotron, 181, 182
- Mass, equivalence of energy and, 189 ff., 209; of nucleus, 187 ff.
- Mass spectrograph, 190, 191
- Mass spectrum, 190
- Matter, particle and wave aspects of, 147 ff.
- Maxwell, Clark, 31-32
- Measurements, used by atomic physicists, 7, 81-91
- Medicine, and radioactivity, 222, 223
- Meson, 135
- Meter, defined, 82
- Millikan, Robert A., 73, 75, 78, 113
- Molecules, effect of alpha particles on, 132-135
- NEUTRON, AND NUCLEAR FISSION, 217 ff.; determining weight of, 194, 195; discovery of, 170-172; nature and properties of, 163 ff.; transformation of, 206 ff.
- Neutrino, 10, 204 ff.
- Nuclear chain reaction, 216, 217, 223
- Nuclear charge, 159
- Nuclear disintegration, 165 ff.
- Nuclear fission, 218 ff.
- "Nuclear fuel," 216
- Nuclear transformation, 165 ff.
- Nuclei, artificial creation of, 206
- Nucleon, defined, 210, 217
- Nucleus, measuring mass of, 189 ff.; present knowledge of, 211, 212; properties of, 137 ff., 162 ff.
- Numbers, method of expressing, 5, 6, 12, 14
- OIL DROP EXPERIMENT, 74-80, 113
- Oxygen atom, as standard of measurement, 191, 192
- PARTICLES, CONCEPT OF, 155, 156
- Periodic system, 159, 212
- Photocells, 106-109
- Photons, defined, 104; properties of, 104, 105, 106, 150, 151

- Piezoelectricity, 70, 71
 Planck's constant, 104, 105, 109, 148, 208
 Polonium, atoms of, 8, 14-16, 56, 63, 113; radioactivity of, 124-134
 "Population pressure," in nucleus, 211, 218
 Positron, 135, 207 ff.
 Potential difference, 90
 Potential energy, defined, 85
 Power stations, atomic, 221
 Prisms, 40, 41
 Protons, defined, 163; properties of, 163 ff., 188 ff.; transformation of, 206 ff.
 QUANTUM MECHANICS, 205 ff.
 Quantum theory, 7, 62, 80, 110-112, 142-146, 160, 161
 RADAR WAVES, 35
 Radiation energy, conversion of, 208
 Radioactivity, artificial, 206; creation of negative and positive electrons from, 203 ff.; of polonium atom, 124 ff.; of uranium, 200, 201
 Radiothorium, atoms of, 11, 12, 14
 Radio waves, 31-35
 Radium, 200, 201
 Radium E, 202-204, 210
 Rasmussen, E., 43, 44
 Relativity, theory of, 112, 193
 Resonance, 29-30
 Rowland, H., 42
 Rutherford, Ernest, 8, 137, 166, 168, 171, 216
 SCHROEDINGER, ERWIN, THEORY OF, 154, 199
 Second, unit of time, 83
 Shell structure, of electrons, 158, 159, 161
 Smyth, H. D., 220
 Sodium chloride, ionization of, 69-71
 Sodium light, wave length of, 36-40, 44
 Solar day, 83
 Spectral lines, 42, 45
 Spectrographs, 40, 41
 Spectrometer, 57
 Spectroscope, 130, 131
 Spiral, of electron, 142, 144
 TELEVISION SCREEN, EFFECT OF MAGNET ON, 97
 Television tube, 93 ff.
 Theory of relativity, 112, 193
 "Tracers," 222, 223
 Transmutation of elements, 130, 131
 ULTRAVIOLET RAYS, 39, 53
 Uncertainty relation, 156, 161
 Uranium, 123, 200, 201, 218-220
 VALENCY, 79
 Van de Graaff machine, 175-180
 Van de Graaff, R. J., 175
 Visible spectrum, 39
 Volt, defined, 90
 Volta, Alessandro, 90
 Voltage, of betatron, 187; of cyclotron, 186; of Van de Graaff machine, 179, 180
 WALTON, E. T. S., 180
 Wave equations, 152-154
 Wave field, 149-161
 Wave function, 152-161
 Wave length, measuring, 36-44
 Wave mechanics, 152-161, 205 ff.
 Waves, electromagnetic, 6, 26-34, 110-112, 141-146, 149, of electrons, 147-161; radio, 31-35; theory of, 155, 156
 Wavy circles, 151
 Weight of atoms, 65, 67, 113-123
 Wilson, C. T. R., 134, 135, 168
 X-RAYS, AND ATOMIC ARRANGEMENT, 58 ff.; diffraction of, 47 ff.; effect on air and other gases, 52, finding wave lengths of, 57-59; "hard" X-rays, 53, 54; in chemical analysis, 160, 161, in treatment of disease, 51, 52; production of, 46, 47; "soft" X-rays, 53; use in study of structure of crystals, 20-25
 X-ray spectrometer, 47 ff.

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